

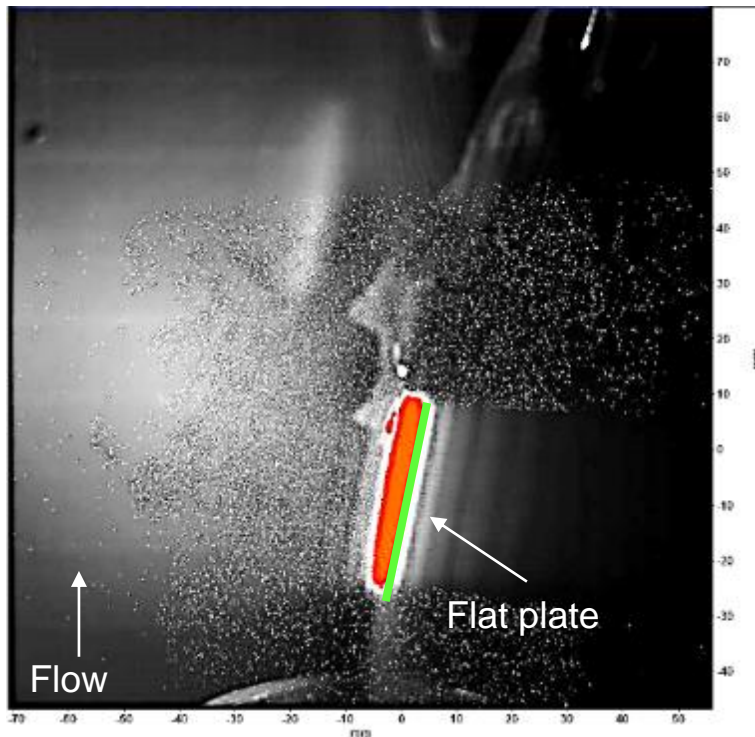


Particle Image Velocimetry Applications of Fluorescent Dye-doped Particles

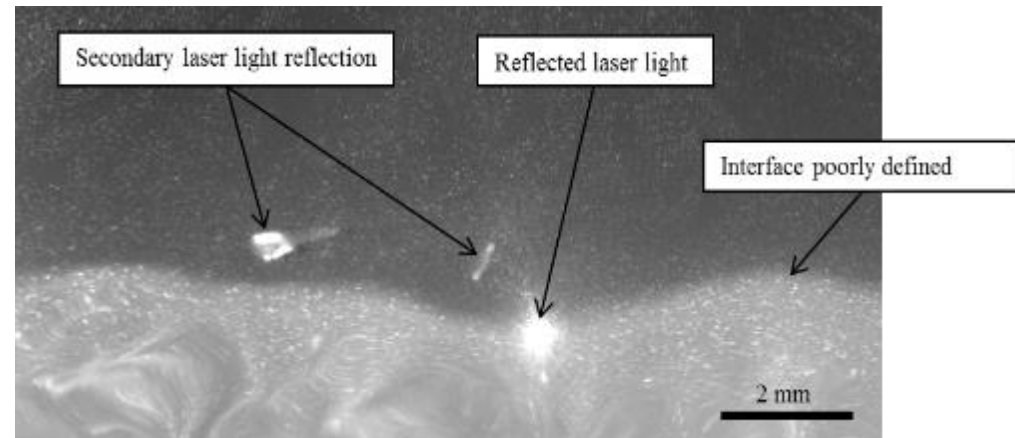
Brian J. Petrosky

1. Introduction
2. Polystyrene Latex (PSL) Particle Characterization
3. Fluorescent Particle Image Velocimetry (PIV) Technique Validation
4. Fluorescent PIV Applications
5. Kiton Red Temperature Sensitivity
6. Summary and Future Work

- PIV measurements use Mie scattered light of seed particles from a laser source.
- Leads to laser flare at solid boundaries or at liquid/gas interfaces.



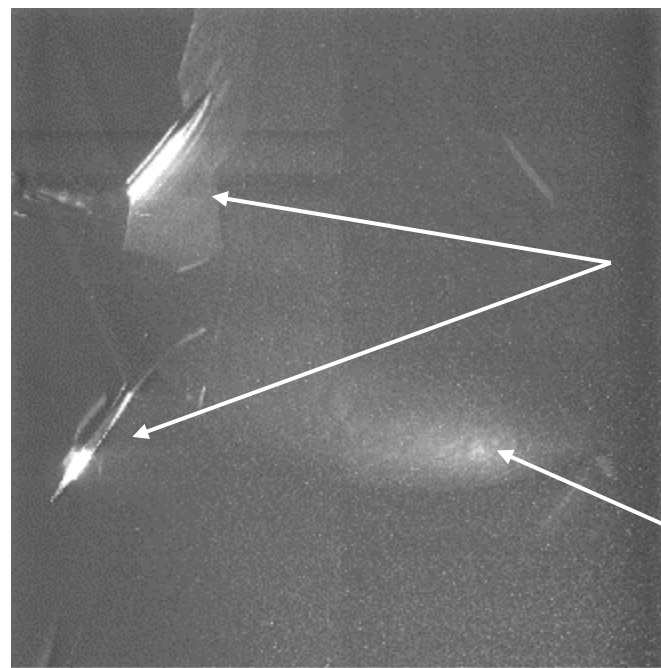
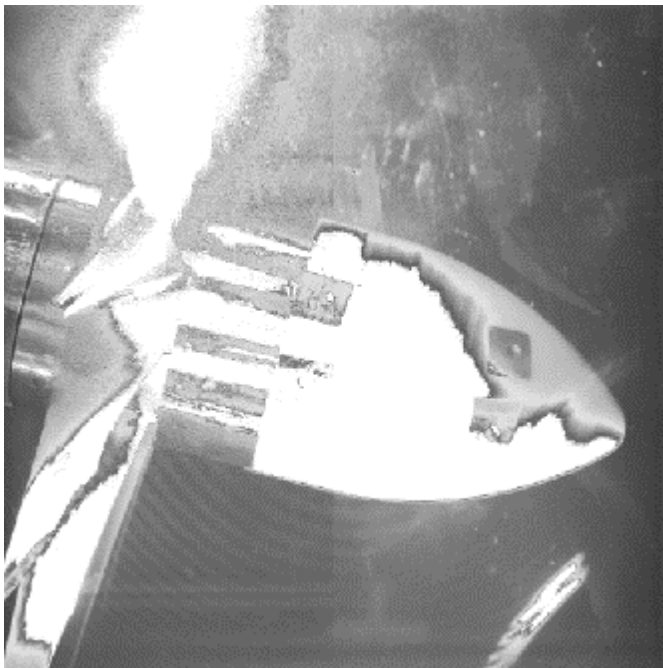
Flow past a flat plate with significant flare near the surface.



Two-phase air/water flow with reflected light at interface.

Surface Flare Reduction Techniques

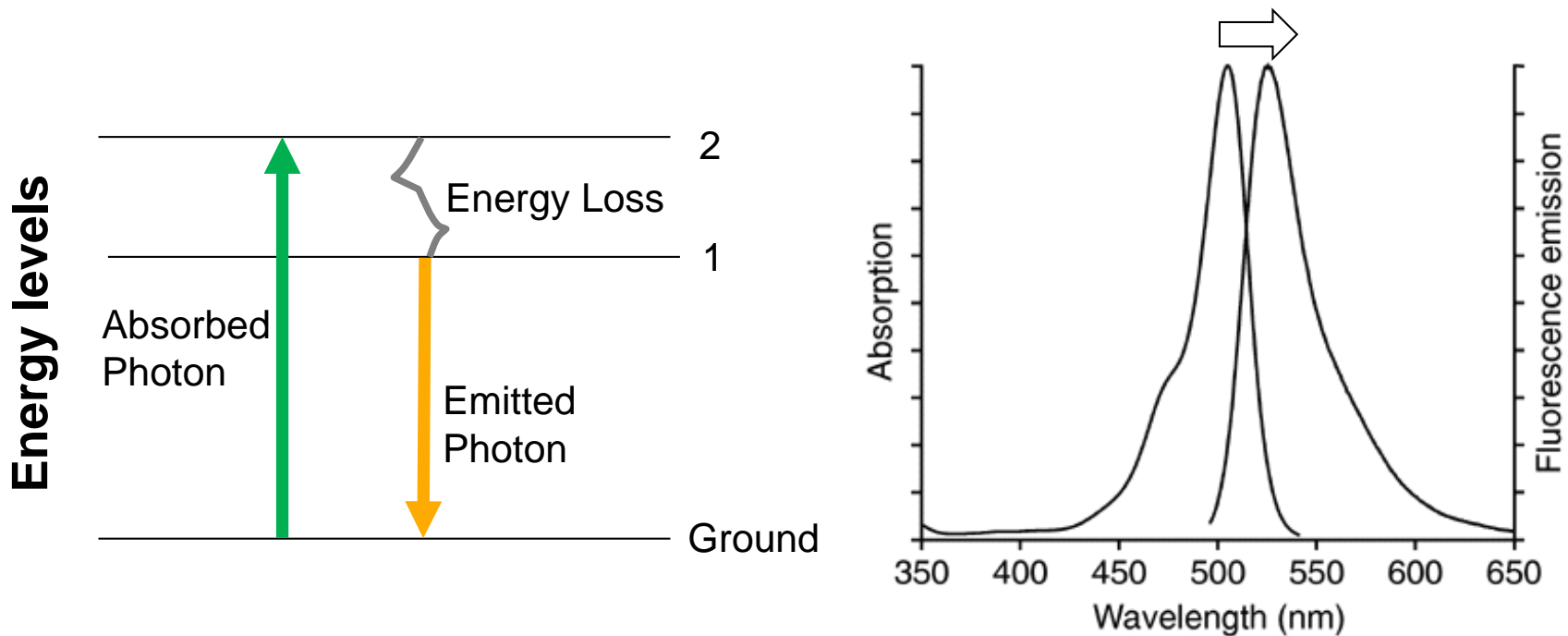
- Black paint is quick solution but not completely effective.
- Surface treatments are expensive, fragile, labor intensive, and/or carcinogenic.
- Flare at air/liquid interfaces is essentially unavoidable.



Aluminum rotor before (left) and after (right) back paint added [1]

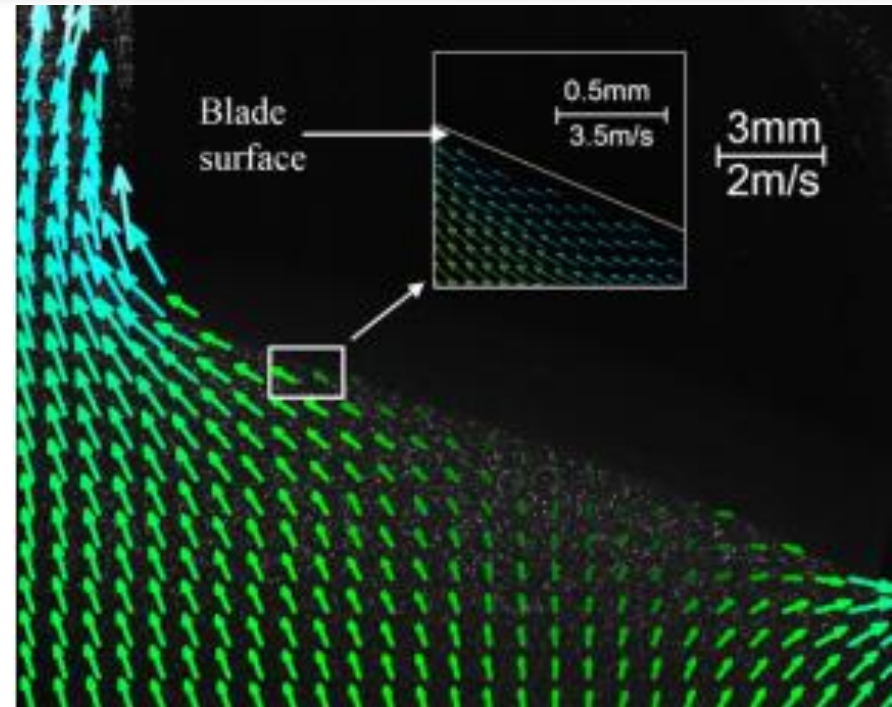
[1] Alexander, W. N., Devenport, W., Wisda, D., Morton, M., and Glegg, S. A. L., "Sound Radiated from a Rotor and Its Relation to Rotating Frame Measurements of Ingested Turbulence", 20th AIAA/CEAS Aeroacoustics Conference, Atlanta, GA, July 16-20, 2014, AIAA-2014-2746.

- Stokes shift: fluorescent light at higher wavelengths than the excitation light
- A high pass optical filter used to block reflections and flare.
- Intensity of fluorescent light given by $I_{\lambda} = I_0 * \alpha(\lambda_0) * \varepsilon(\lambda) * N_M$



The Stokes shift.

- Fluorescent light for PIV is common in water flows [2,3] or micro PIV [4,5].
- In water, acceptable particle diameters are much larger than in air.
- Very few fluorescent PIV measurements conducted in air:
 - Most involve two phase-flow or fuel injection
 - Some used large particles [6]
 - The most successful, by Chennaoui et. al, demonstrated the potential benefits of this technique but used dangerous particles[7].

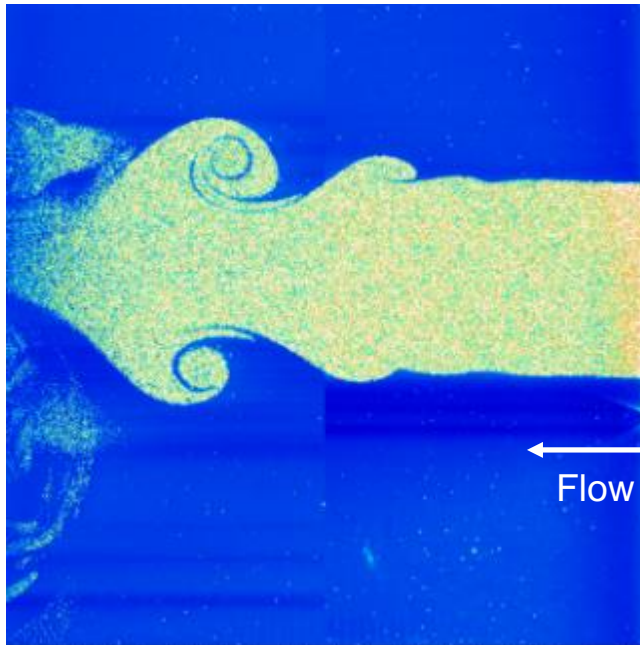


PIV obtained via Microscatterlight [8][8].

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- [2] Poussou, S., and Plesniak, M. W., "Near-Field Flow Measurements of a Cavitating Jet Emanating From a Crown-Shaped Nozzle"
- [3] Lozano A, Barreras F, Fueyo N and Santodomingo S, "The Flow in an Oil/Water Plate Heat Exchanger for the Automotive Industry"
- [4] Wereley S and Meinhart C D, "Recent Advances in Micro-Particle Image Velocimetry"
- [5] Singh A K, Cummings E B and Throckmorton D J, "Fluorescent Liposome Flow Markers for Microscale Particle-Image Velocimetry"
- [6] Towers, Dd. P., et. al., "A Colour PIV System Employing Fluorescent Particles for Two-Phase Flow Measurements"
- [7] Chennaoui, M., D. Angarita-Jaimes, M. P. Ormsby, N. Angarita-Jaimes, E. McGhee, C. E. Towers, A. C. Jones, and D. P. Towers. "Optimization and evaluation of fluorescent tracers for flare removal in gas-phase particle image velocimetry." Measurement Science and Technology", Vol. 19, no. 11 (2008): 115403.

- Manufacture and conduct PIV experiments using fluorescent particles in an airflow.
- Requirements:
 - Particles must be small (generally $< 2\ \mu\text{m}$).
 - Particles must display an adequate fluorescence signal.
 - Particles must be relatively safe for use in an open environment.



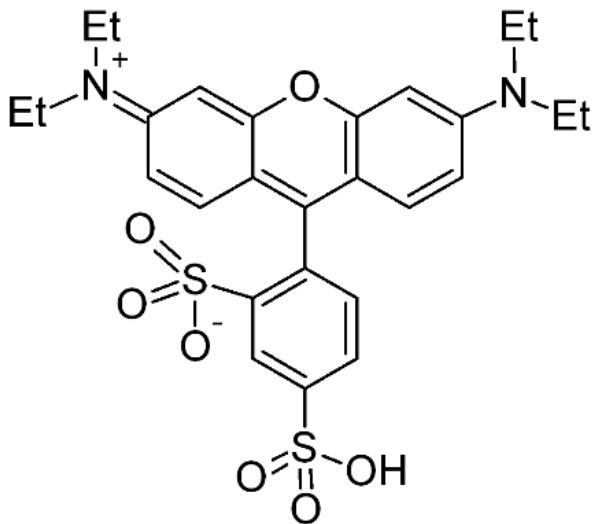
Flow from a seeded nozzle at 3.5 m/s.



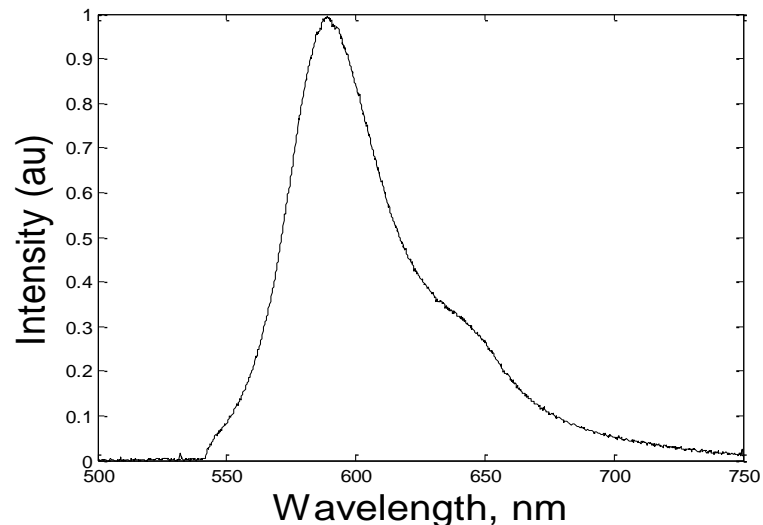
Wind tunnel test section. From NASA.gov [8].

Kiton Red Doped PSL Particles

- Produced at NASA Langley via dispersion polymerization
- Past Virginia Tech research has used Rhodamine B, Dichlorofluorescein (DCF), and Kiton Red 620 PSLs
- Highest signal obtained from Kiton Red particles
- These Kiton Red dye-doped particles are:
 - Small, lightweight, and mono-disperse, with a mean diameter of .87 μm
 - Relatively safe to use in an open-air environment, with no carcinogenic effects



Kiton Red molecular structure [9].



Measured Kiton Red emission spectrum at 532 nm excitation.

[9] Walker, Martin. "Sulforhodamine B." *Wikipedia, The Free Encyclopedia*. <http://en.wikipedia.org/wiki/Sulforhodamine_B>



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3. *Fluorescent PIV Technique Validation*

Paper 1

Particle Image Velocimetry Applications Using Fluorescent Dye-doped Particles

*by B Petrosky, P Maisto, K T Lowe, M André, P
Bardet, P Tiemsin, C Wohl and P Danehy*

**Presented at AIAA SciTech 2015
January 5-9, 2015
Kissimmee, FL**

Virginia Tech “Free Jet” Fluorescent PIV Setup

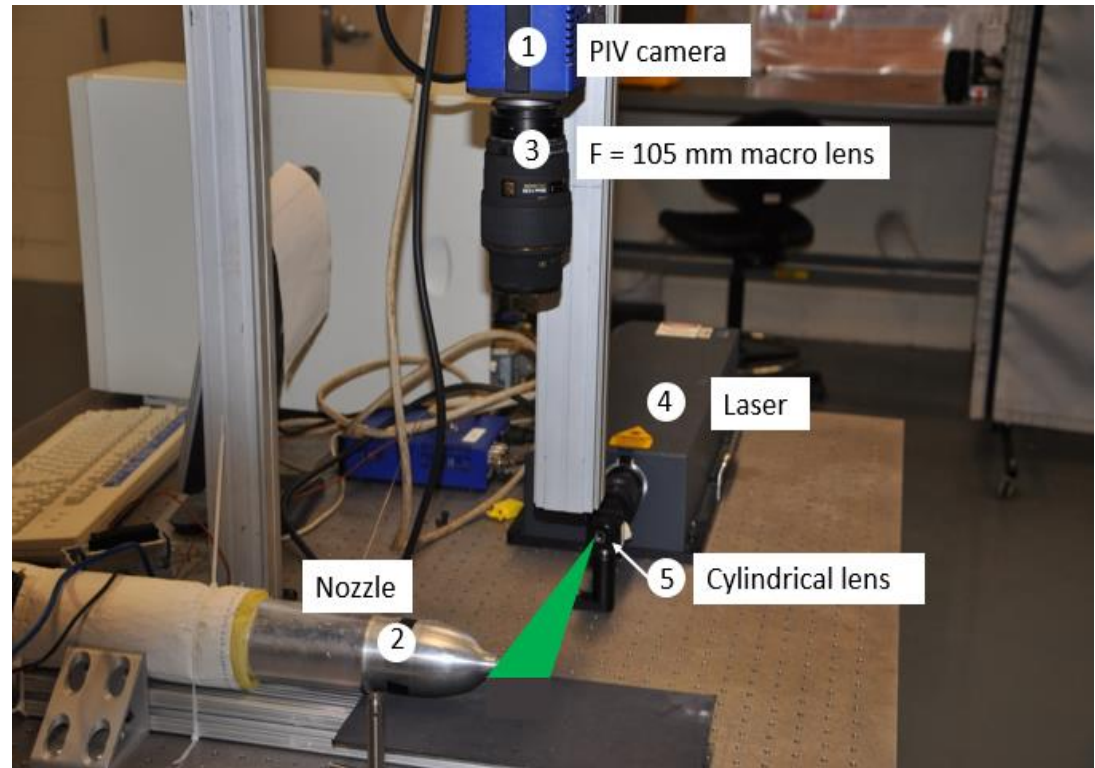
➤ Equipment:

- 2048 x 2048 pixel camera
- Dual-pulsed 532 nm Nd:YAG laser operating at 200 mJ/pulse
- Custom nozzle with exit diameter $d = 14.15 \text{ mm}$ ($\sim 0.55 \text{ in.}$)
- 560 nm long pass filter
- Camera and laser controlled by LaVision's DaVis software, operating at 10 Hz

➤ Test conditions and procedure:

- Fluorescent and Mie scattered images were taken back to back
- Lens aperture set at f/22 for Mie images and f/2.8 for fluorescence

➤ Additional details found in thesis text

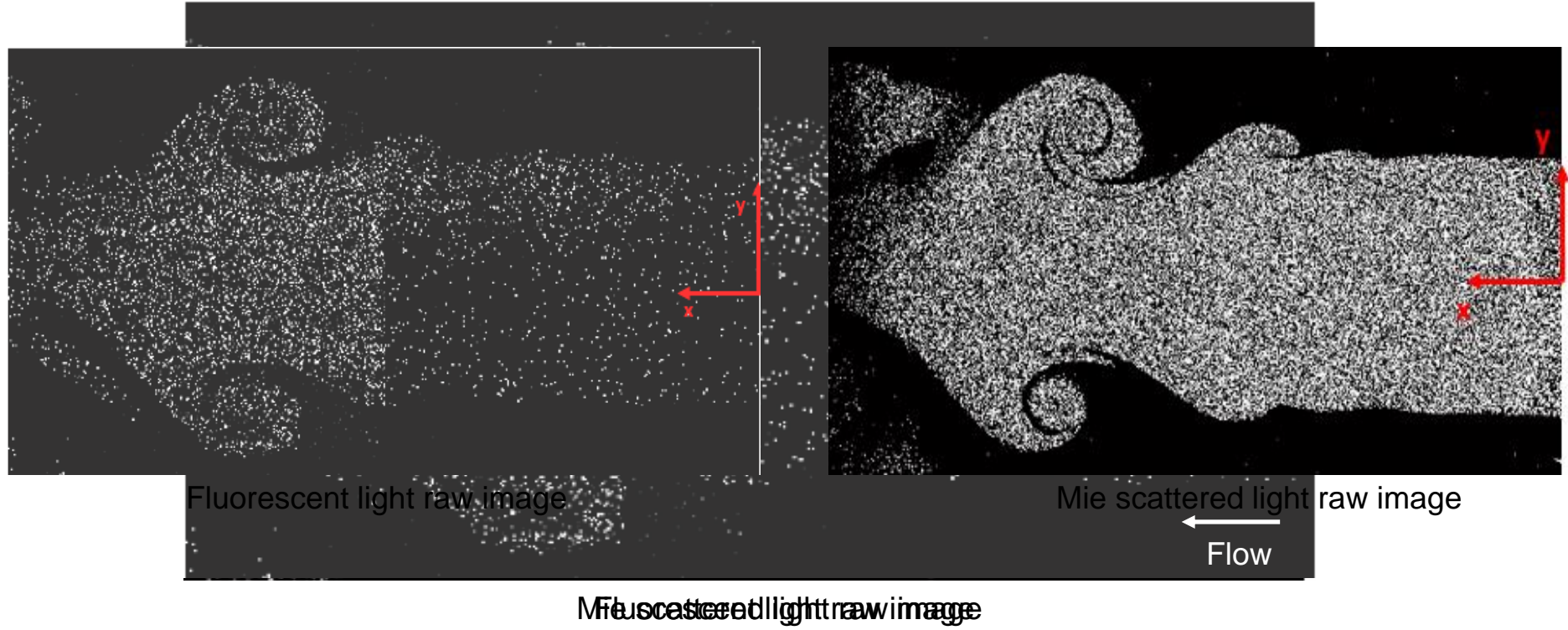


Virginia Tech PIV Setup

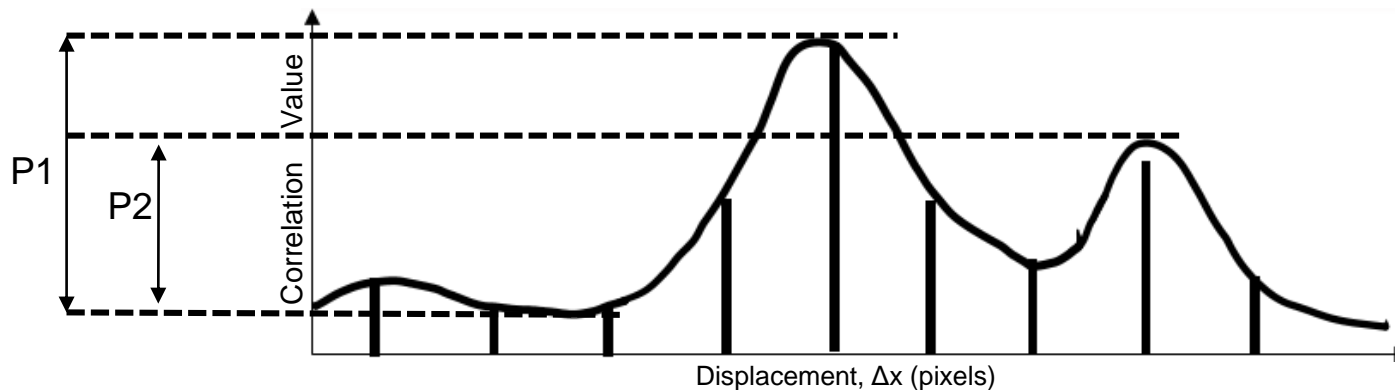
Free Jet Image Comparison- Mie vs. Fluorescence

- Flow is from right to left, ~ 3.5 m/s
- 45.6 mm x 45.6 mm field of view.
- Fluorescence signal clearly lower than Mie signal.
- Whether this lower signal impacted PIV processing would have to be studied.

← 45 mm →



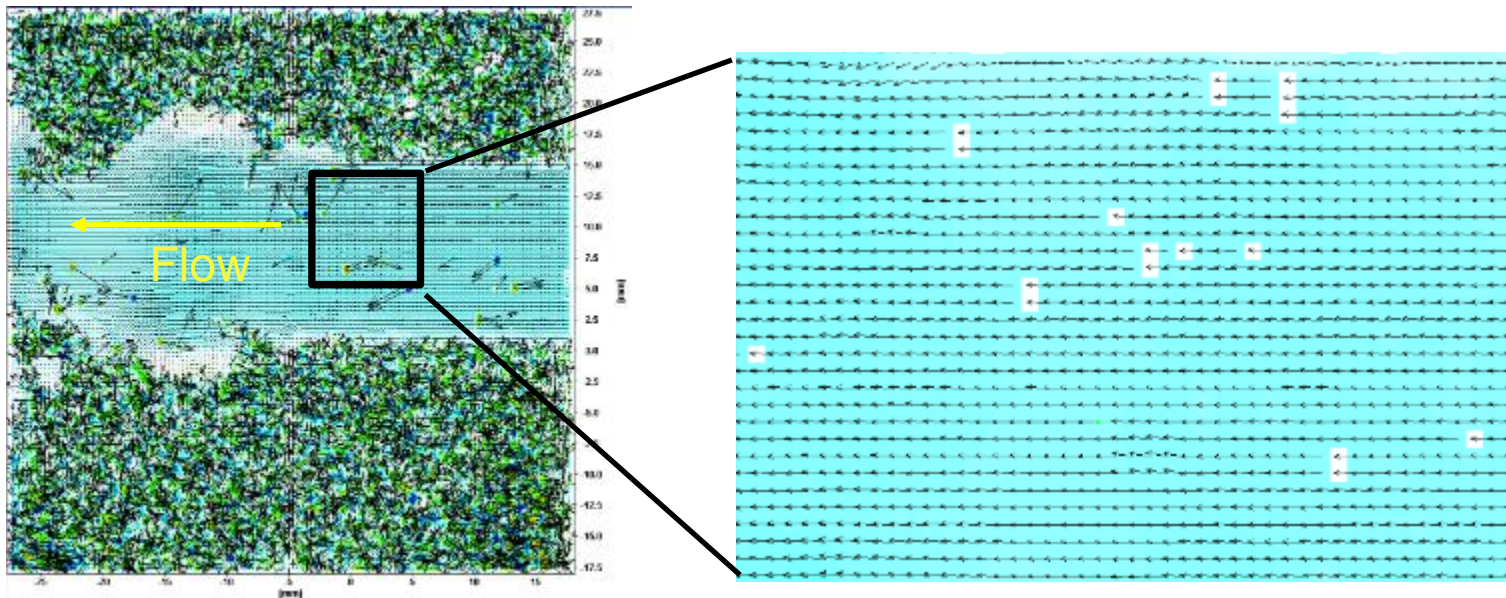
What is Peak Ratio?



Example cross correlation result (oversimplified 1D version)

- Peak Ratio: $Q \equiv \frac{\text{Highest Correlation Peak Height}}{\text{Second Highest Correlation Peak Height}} = \frac{P_1}{P_2}$
- A high peak ratio indicates a clear particle displacement
 - $Q > 1.3$ generally used for “valid” peak.
- The lowest uncertainties in displacement occur for $Q > 2$.
- Low peak ratios indicate a weak signal/excessive noise
- Spurious Vector- vector calculated from an invalid correlation peak.

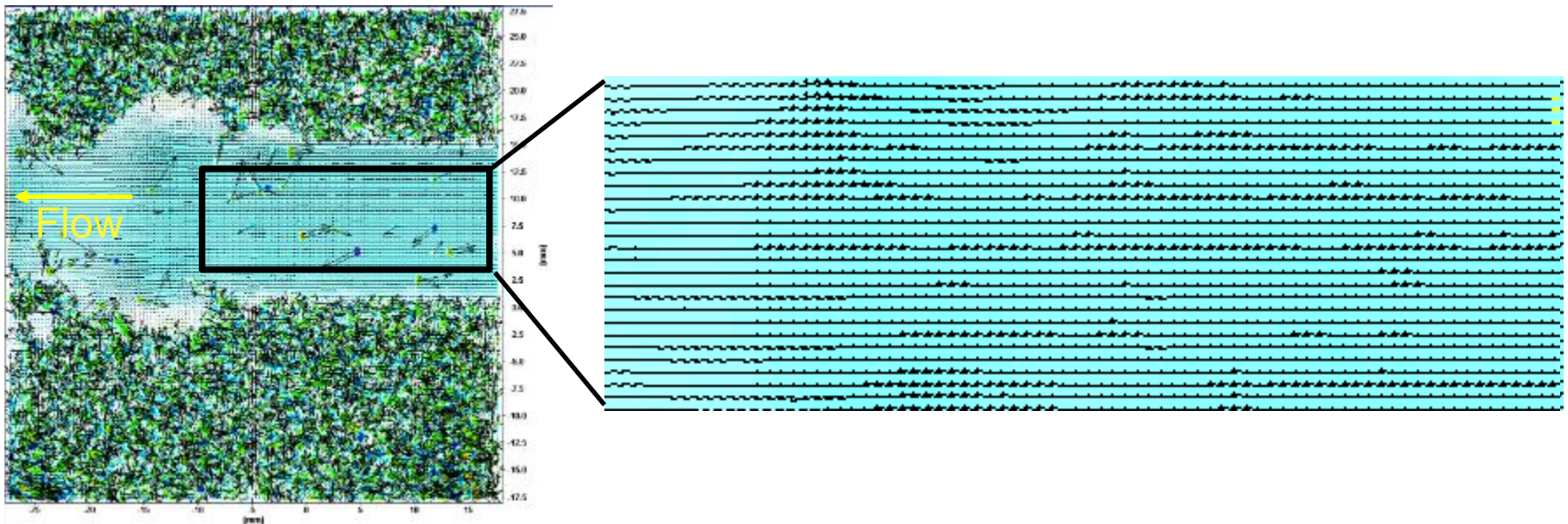
- Percent of spurious vectors compared for Mie and fluorescent images.
- Spurious vectors identified through two steps:
 - Using a median filter, standard for PIV [10].
 - Deleting all vectors with a peak ratio below 1.3.



Spurious vectors calculated from a single pass of a fluorescent image pair.

Spurious Vector Comparison- Results

- Overall, 100% of Mie vectors in the jet were valid, compared to 98.2% of the fluorescent vectors.
 - 95% is often considered the threshold for good quality PIV data. [10]
- Spurious vectors are easily replaced by another correlation peak or interpolated over.



Spurious vector identification and correction.

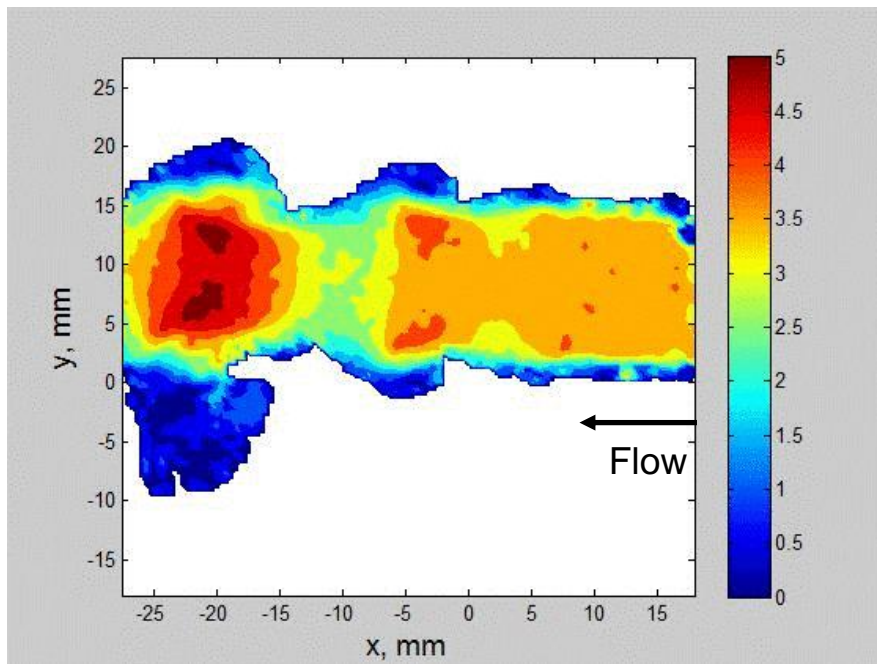
[10] Adrian, R and Westerweel, J. *Particle Image Velocimetry*, Cambridge University Press, New York, 2011.

➤ Processing Methodology:

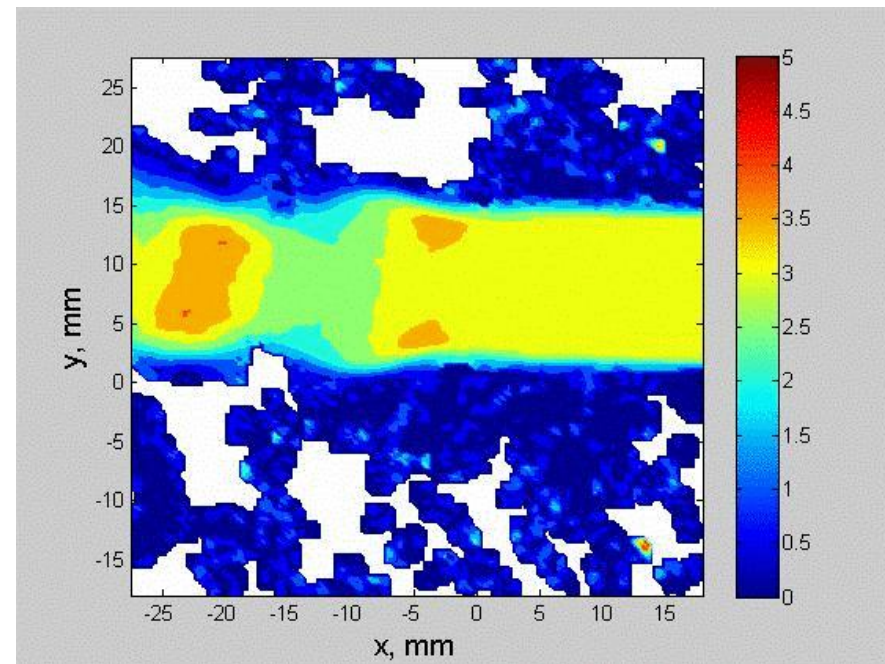
- Multipass technique with 50% overlap
- Spurious vectors removed and replaced via median and peak ratio filter.

- An average of 6000 total vectors per image with a spatial resolution of $356\text{ }\mu\text{m}$.

Velocity Magnitude, m/s



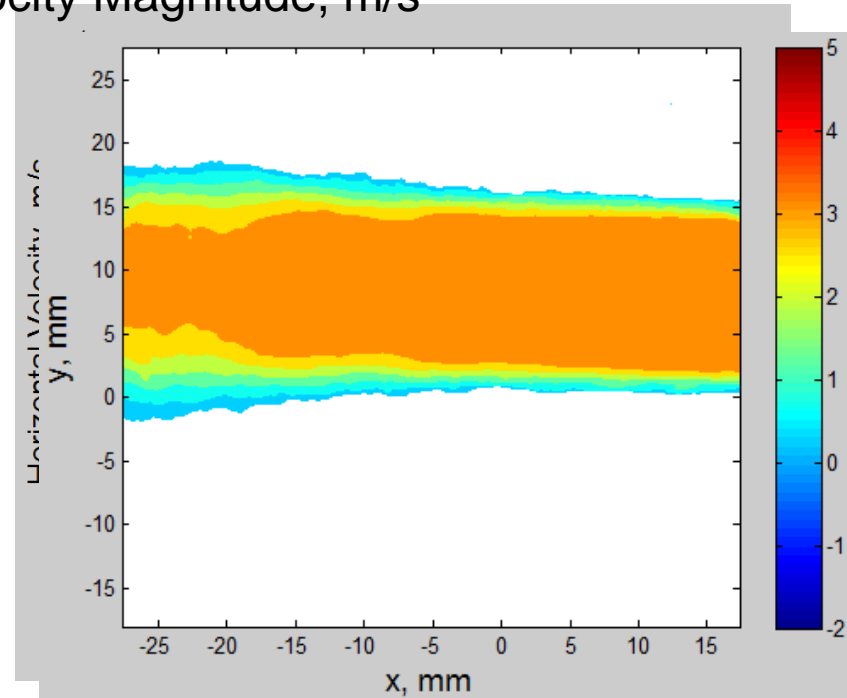
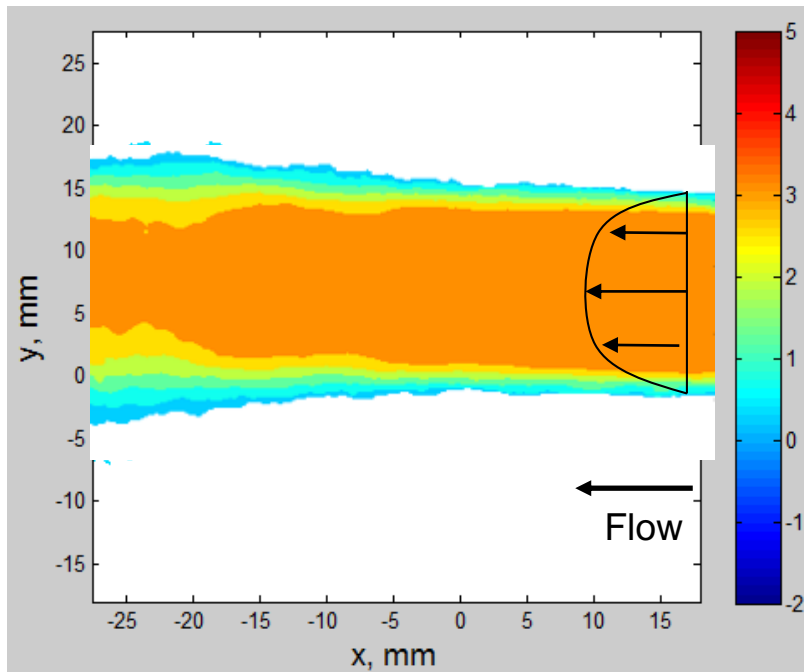
Fluorescent processing results



Mie scattering processing results

- The horizontal exit velocity averages of the jet are within 3% of each other (seen below).
- High peak ratios and correlation values from both image sets.
- Velocity profile across nozzle exit compared.
- Higher velocity values from fluorescence signal likely due to nozzle unsteadiness.

Horizontal Velocity Magnitude, m/s

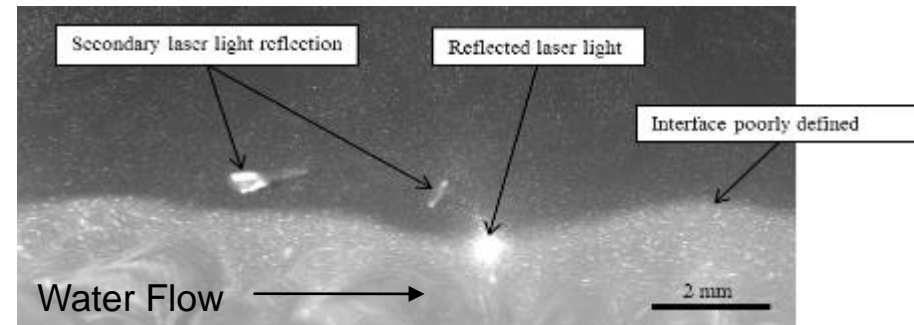


Horizontal Velocity Profile at Nozzle Exit.
Mie scattering (left) and fluorescent (right) horizontal velocity averages.

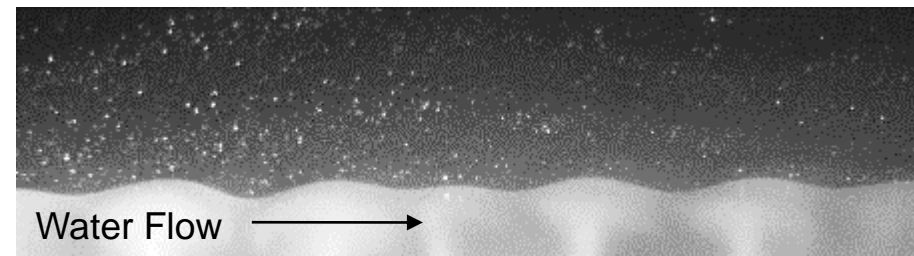
The schematic illustrates the experimental setup for Planar Image Velocimetry (PIV). A water jet containing reflective particles (rhodamine 6G) exits a nozzle at a height of 70 mm from the channel bottom wall. The jet has a diameter of 15 mm and a velocity $U = 2.72$ m/s. The distance from the nozzle exit to the measurement plane is $t_{jet} = 20.3$ mm. Above the jet, fluorescent particles are introduced through a flow straightener. Two green laser sheets intersect at the measurement plane, which is defined by two overlapping fields of view (FOV1 and FOV2). Laser 1 is used for Gas Phase PIV, and Laser 2 is used for Liquid Phase PIV. The surrounding air is quiescent.

- # George Washington University PIV Setup

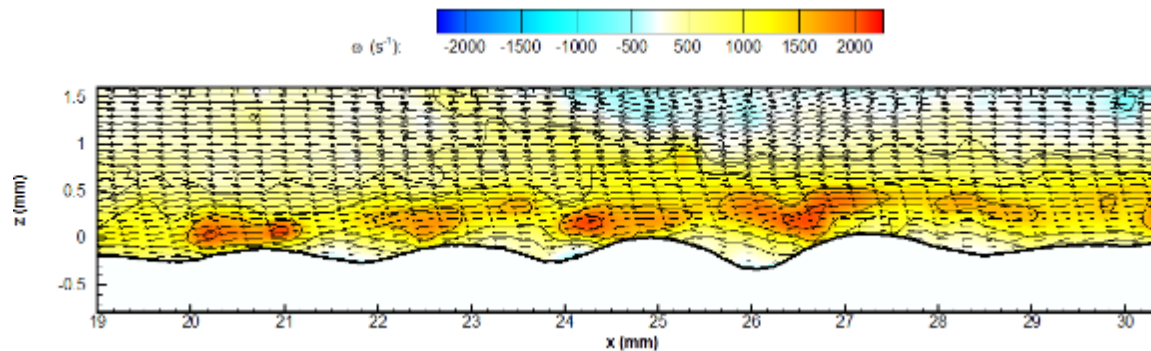
- Reflected light at water surface filtered out
- Velocity vectors obtainable throughout entire air/water interface
- Processing Methodology:
 - Multipass technique with 75% overlap, with a 64x64 pixel first pass followed by 32x32 pixel second pass
 - Spurious vectors deleted via median filters after each pass, replaced via interpolation.



Mie scattering image using reflective particles.



Fluorescent light raw image.



PIV velocity field and vorticity contour plot.



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4. *Fluorescent PIV Applications*

Paper 2

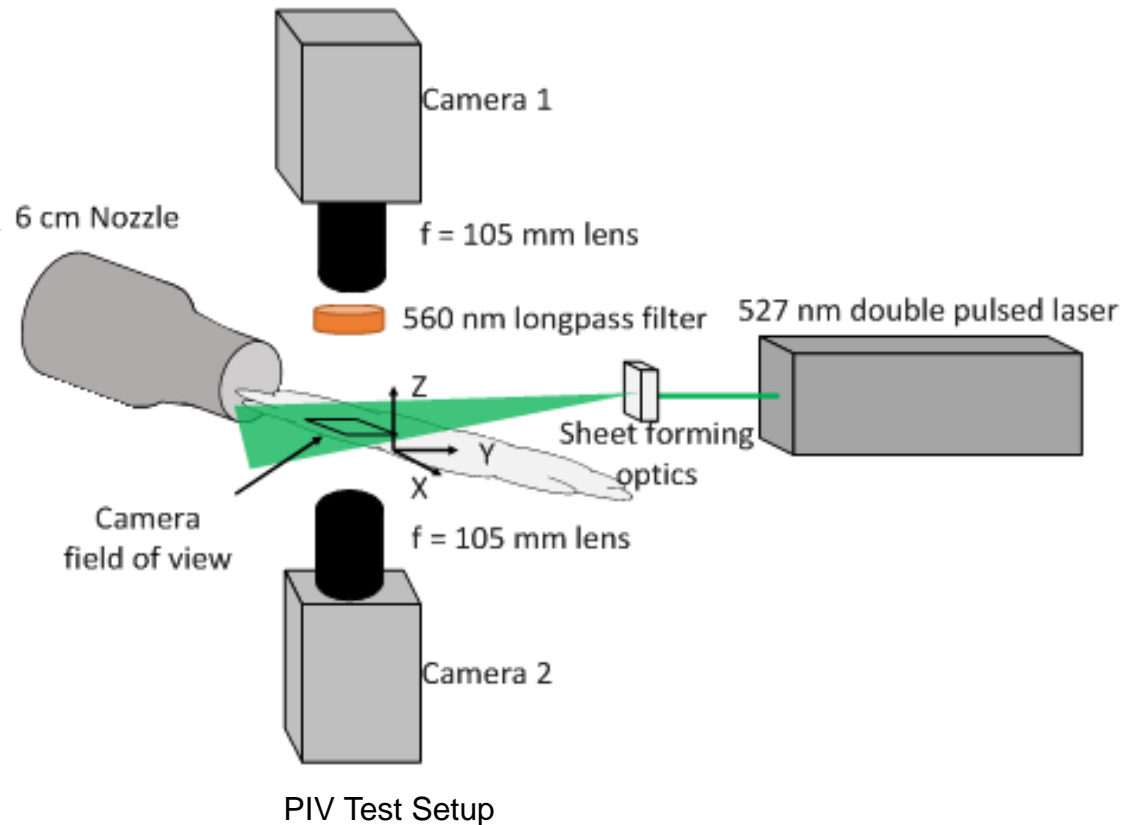
Laser Flare Removal in Particle Image Velocimetry Using Fluorescent Dye-doped Particles

B Petrosky, K T Lowe, P Danehy, C Wohl, and P Tiemsin

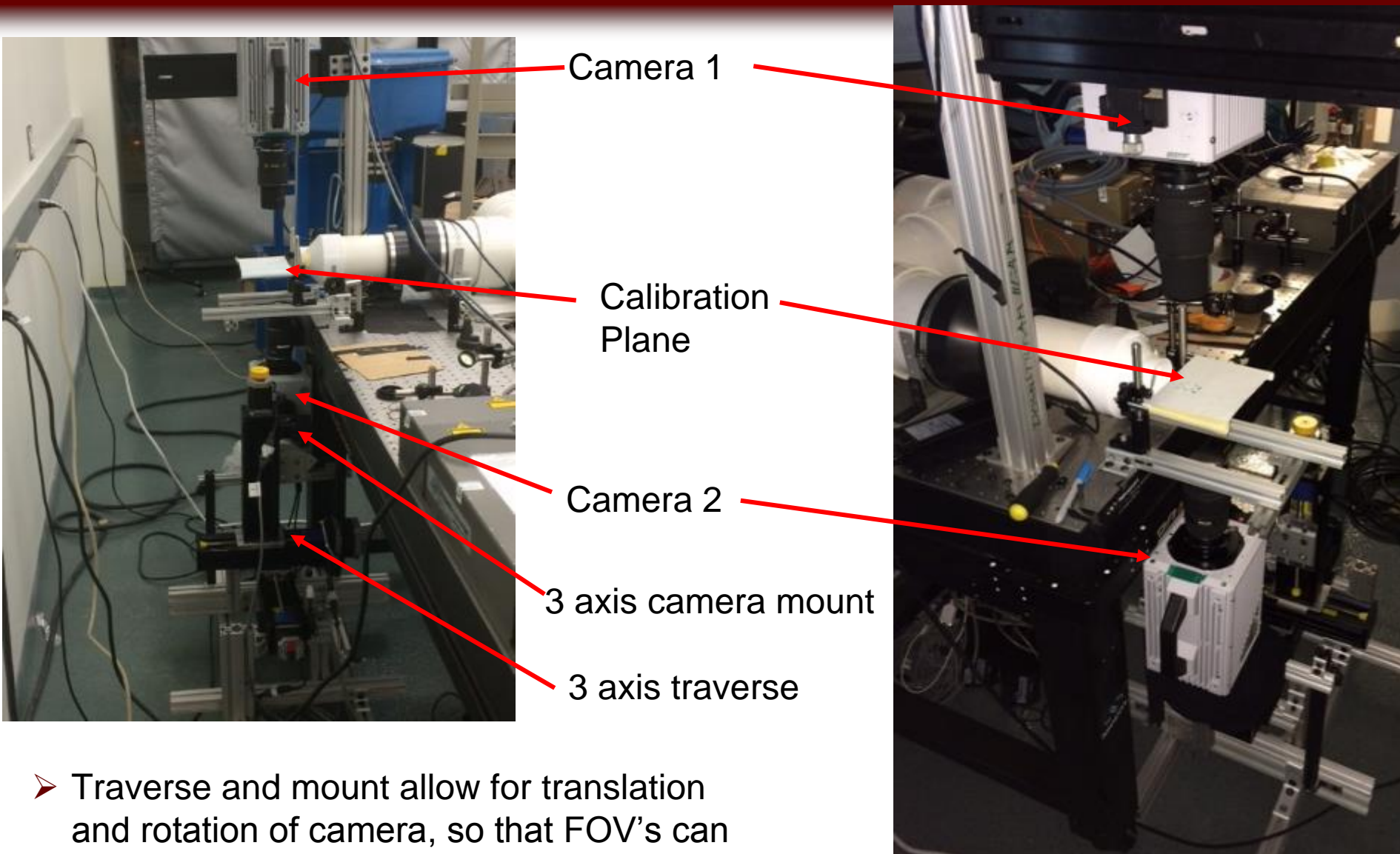
To be Submitted to Measurement Science and Technology

➤ Equipment:

- 1024 x 1024 pixel cameras, 12 bit digitization
- Dual-pulsed 527 nm Nd:YLF laser operating at 23 mJ/pulse
- 6 cm nozzle exit diameter
- 560 nm long pass filter
- Camera and laser controlled by LaVision's DaVis software, operating at 2.5 kHz
- Additional details found in thesis text



Test 1: 2 Camera Mie/Fluorescence Signal Comparison



- The two images are very similar, but slightly off in terms of field of view and orientation.
- Images taken in free air at low speed (~ 8 m/s)

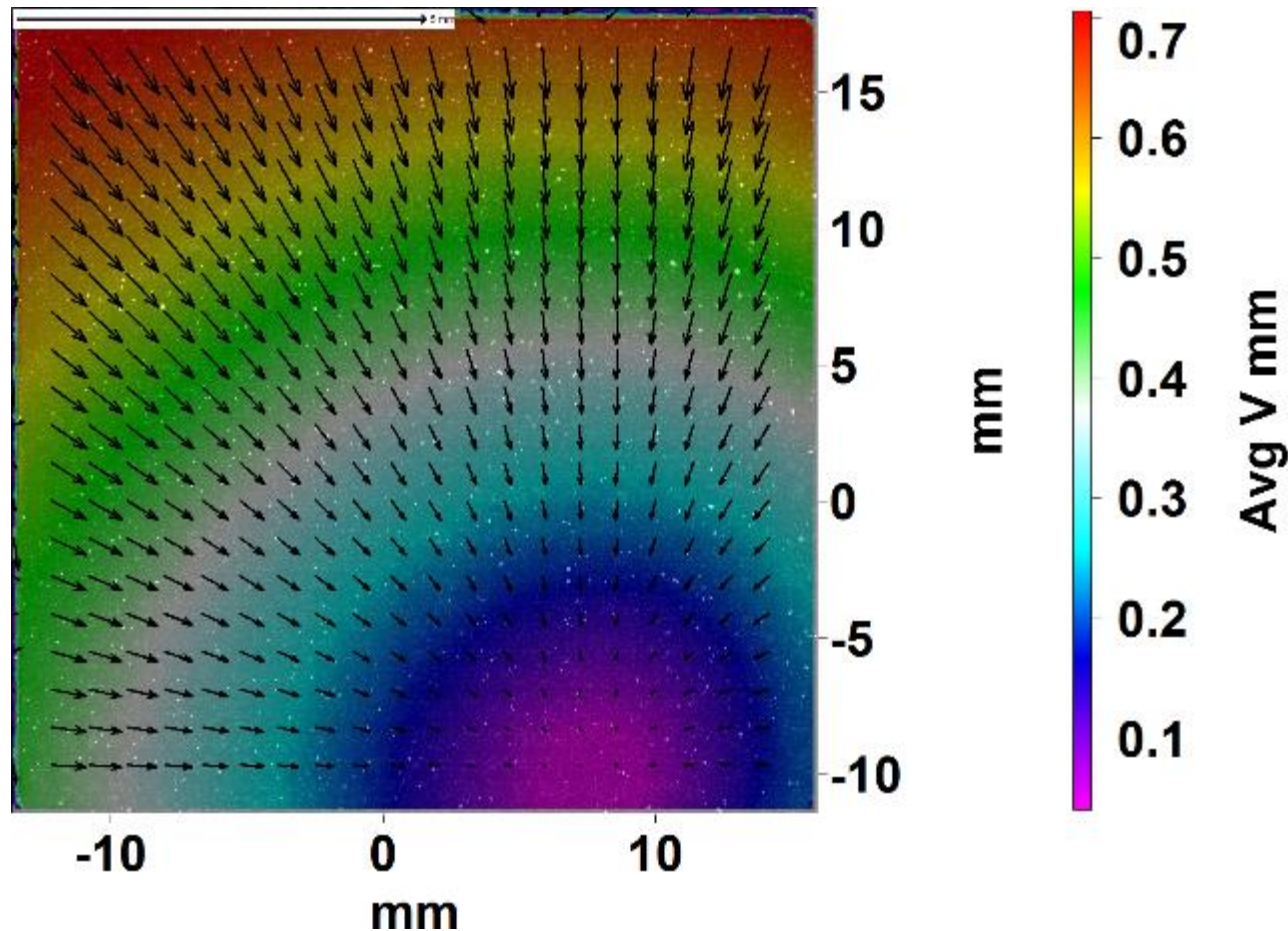
Fluorescence f/2.8

Mie f/22



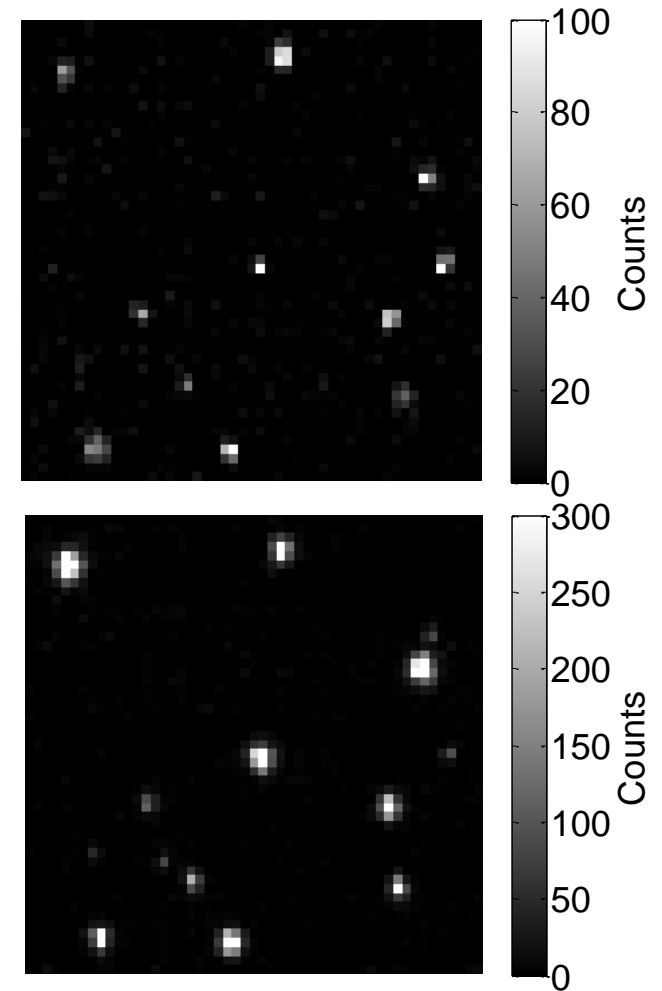
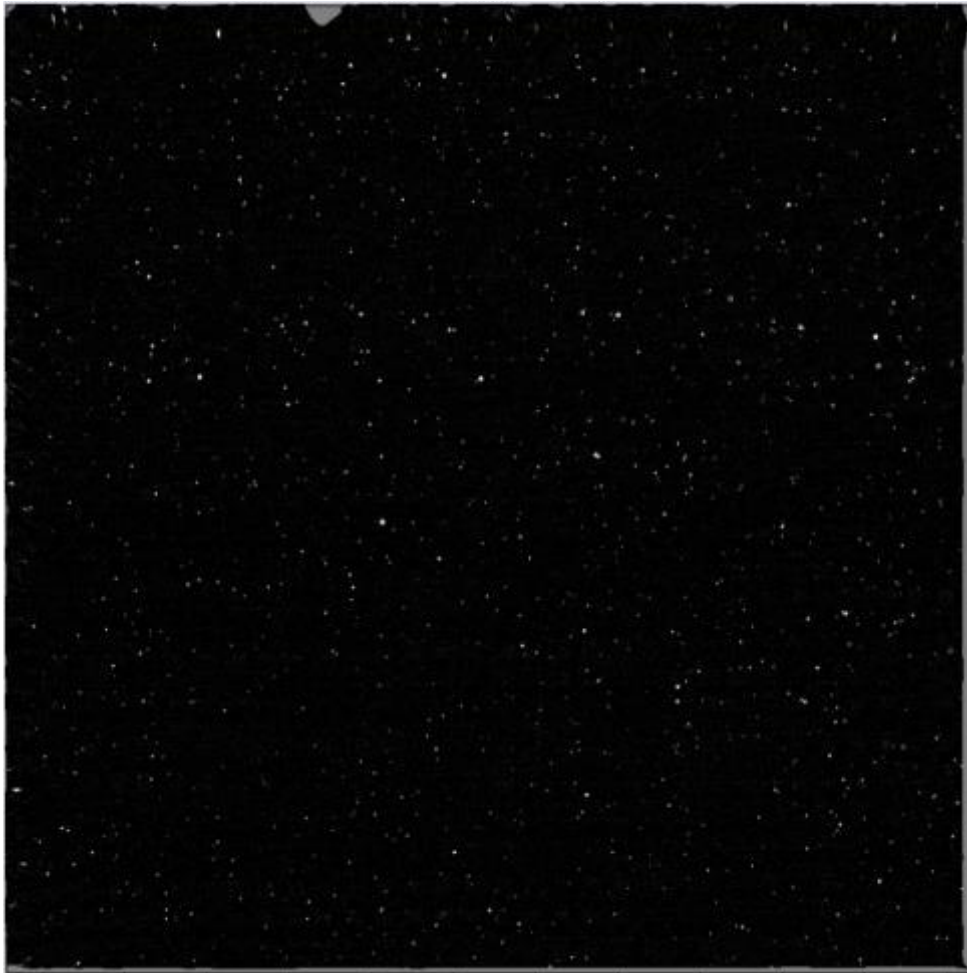
2 Camera Imaging Cross Correlation

- Cross correlation from fluorescence to Mie images determined offset.
- Fluorescent images deformed by this vector field using DaVis.
- Resulting images nearly exactly overlapped with the Mie images.



2 Camera Imaging: Final Overlapping Images

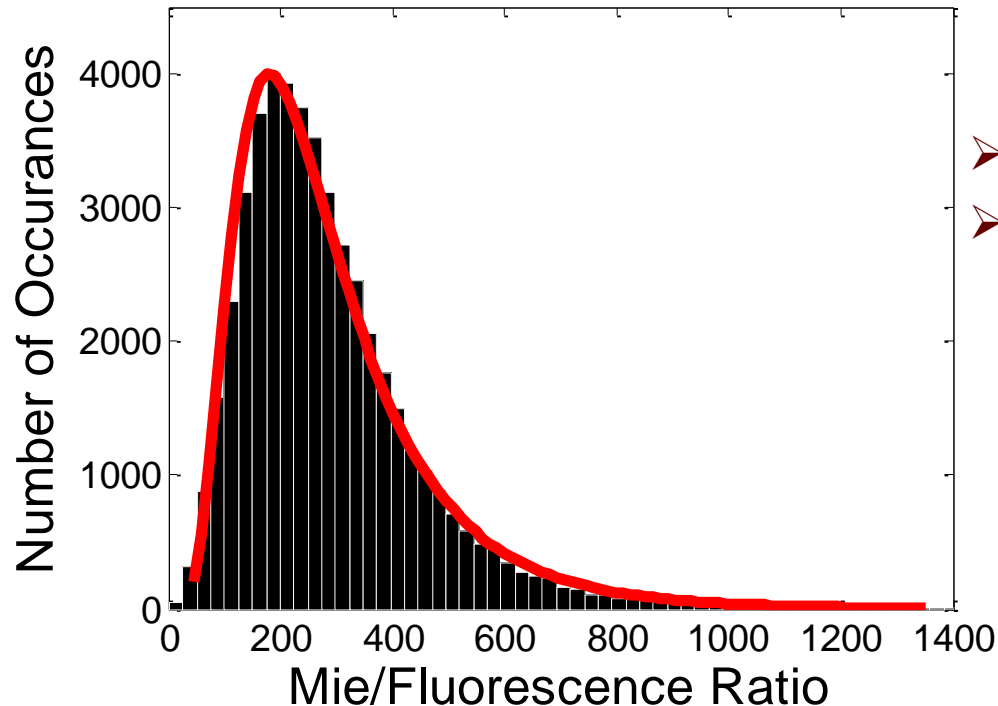
Fluorescence f/2.8
Mie-scattered



50 x 50 pixel image of fluorescence image (above) and Mie-scattered image (below).

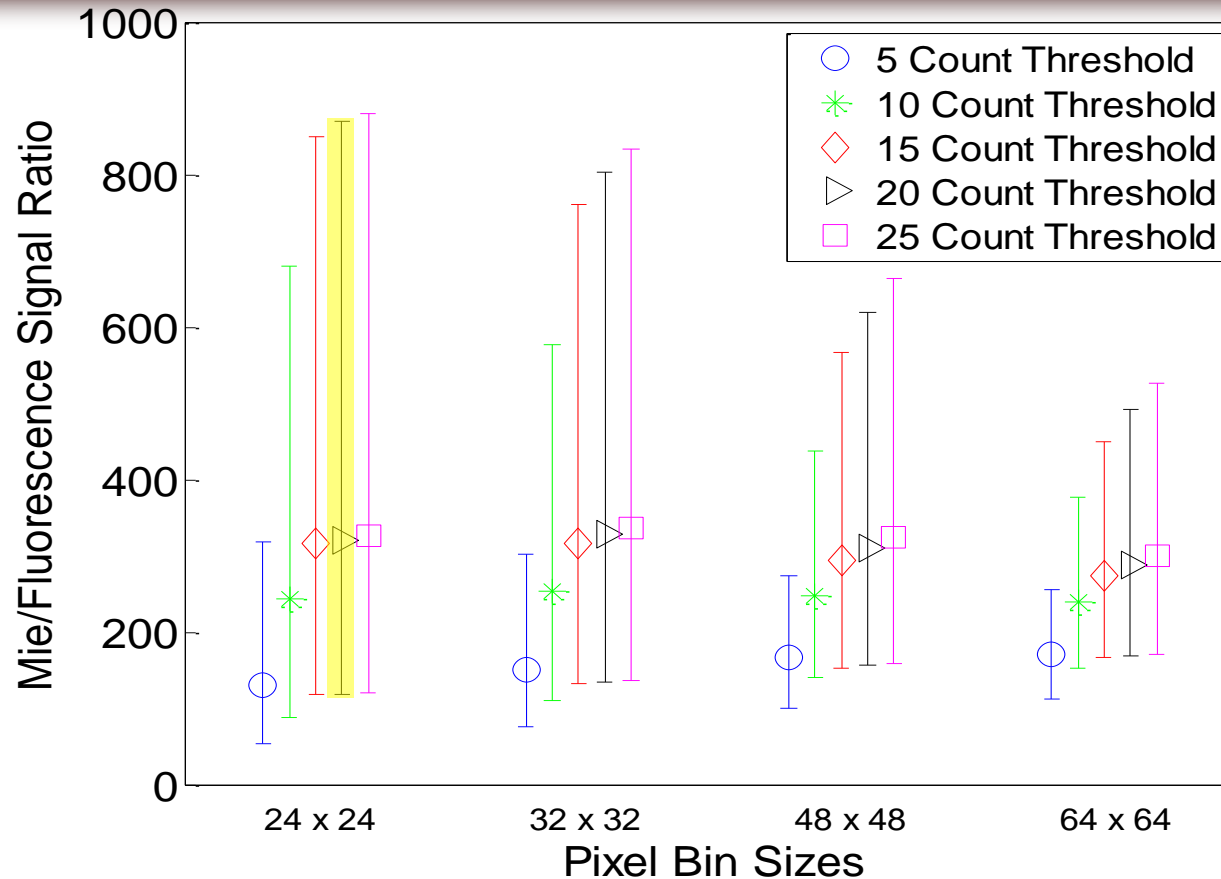
- Images broken up into square bins
- Minimum pixel count threshold used to differentiate valid signal and noise.
- Ratio between the Mie and fluorescent signal was taken for 150 images

48 x 48 bin sizes, 10 count minimum signal

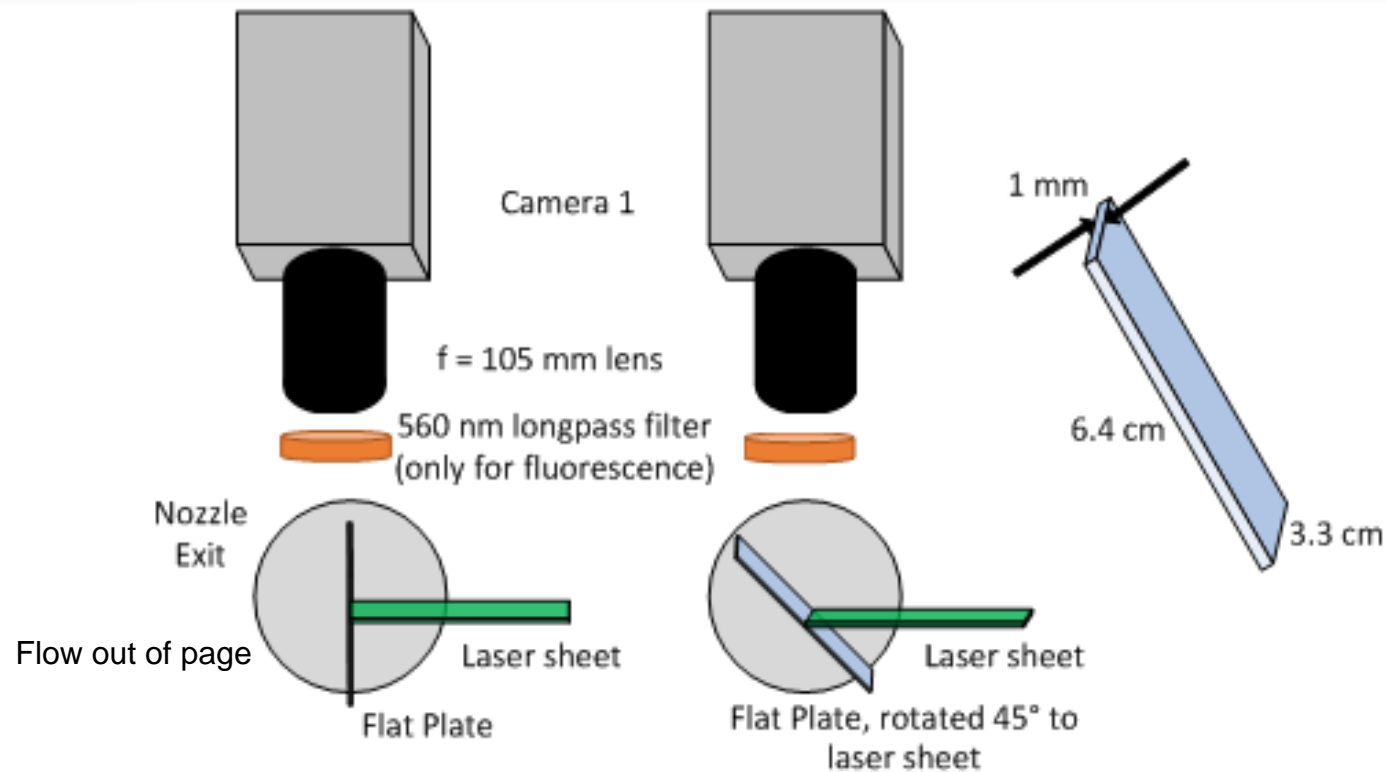


- Histogram distribution is lognormal.
- Distribution described using geometric mean and standard deviation.

Mie/Fluorescence Signal Analysis



- 24 x 24 bin size (highlighted) chosen to describe the particle signal characteristics.
- Mean signal is 321 ± 12 times stronger in Mie.
- Expected individual particle signal ranges from 120 and 870.
- Variation suggests a degree of nonuniformity in dye concentration.



- Aluminum flat plate placed in 4.5 m/s flow.
- Plate used in 2 orientations, as shown. Both were set to approximately a 0° AoA.
- Only a single camera was used for these tests.
- Fluorescence and Mie data sets taken back to back, rather than simultaneously.

Plate Orientation 1: Plate Perpendicular to Sheet

- Raw images for fluorescent and Mie techniques.

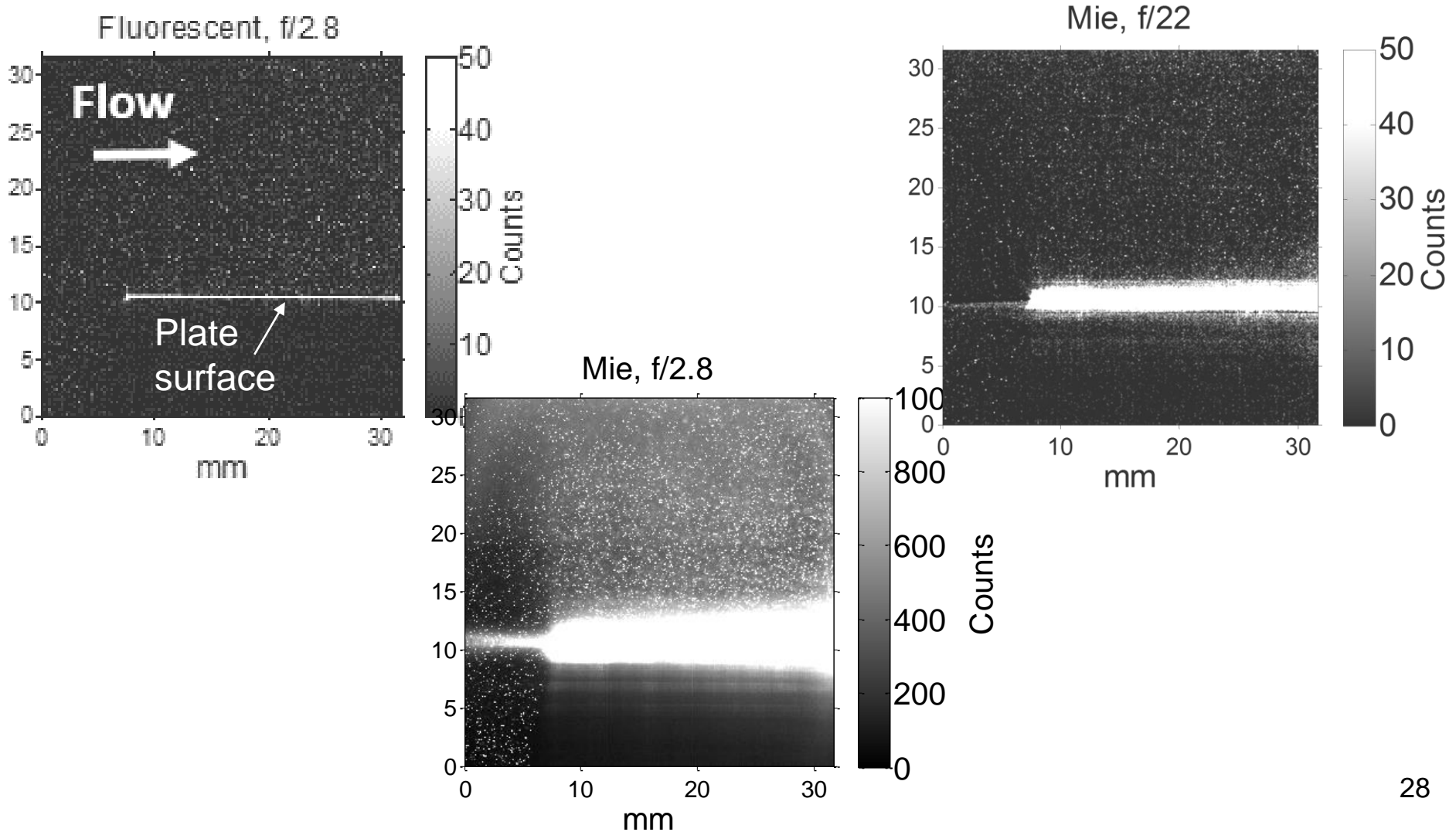


Plate Orientation 1: Processing Results

➤ Vectors processed with 24 x 24 final pass interrogation window sizes.

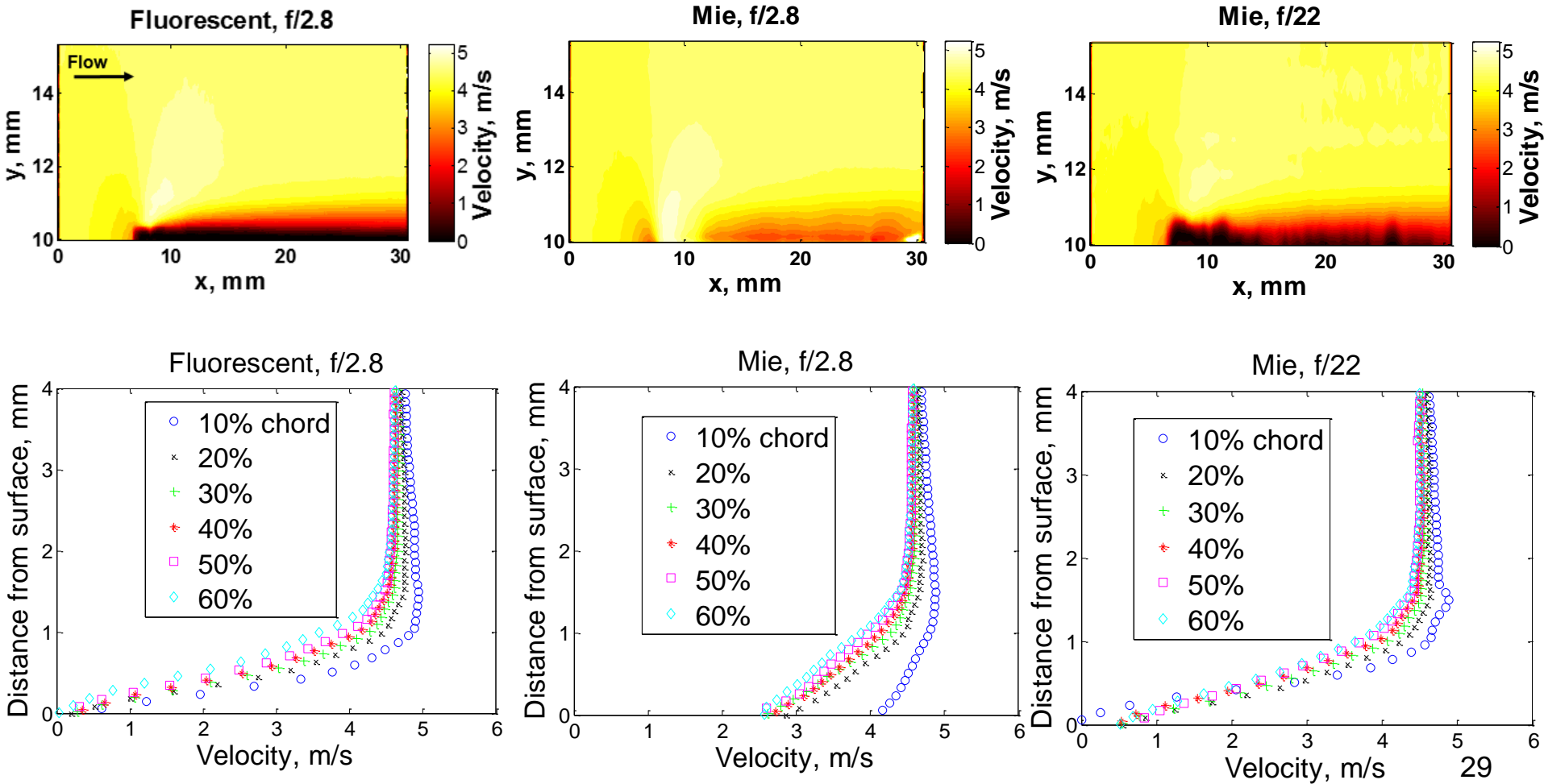
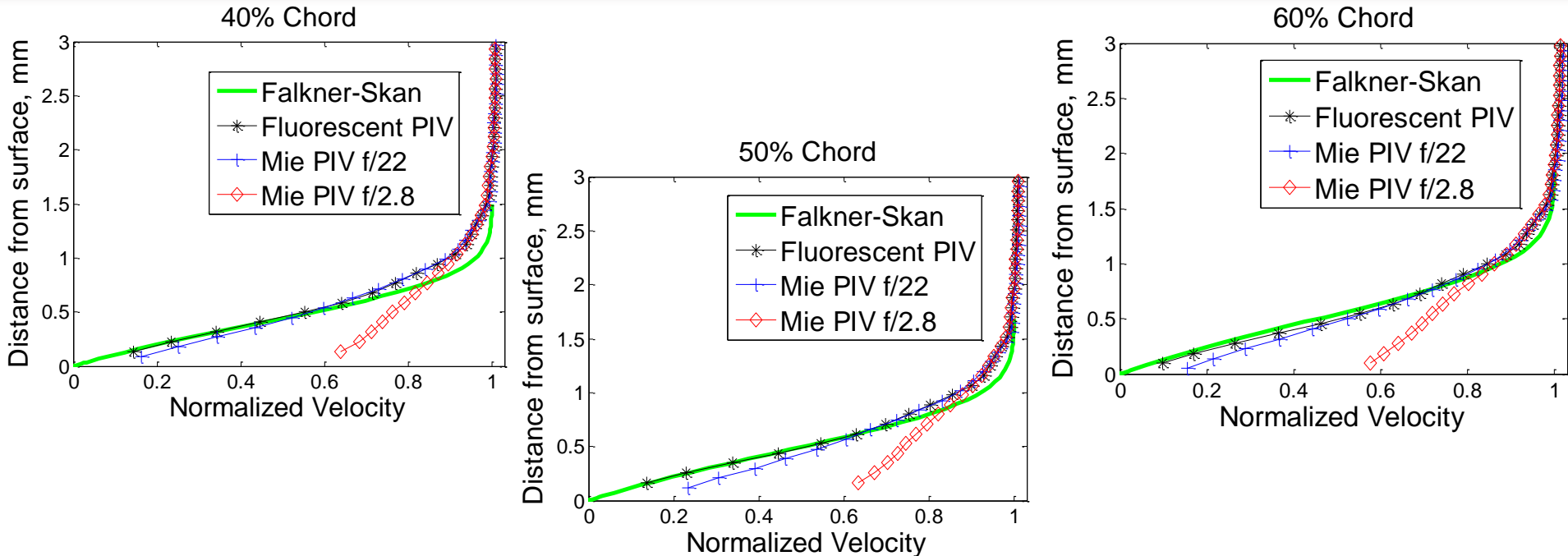
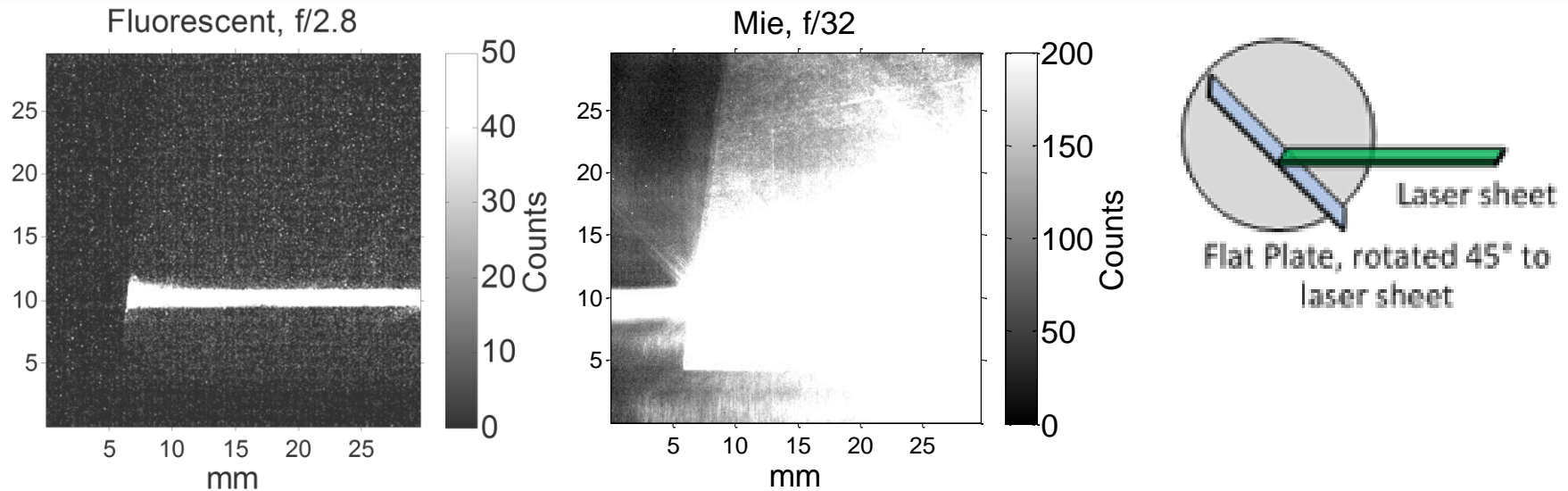


Plate Orientation 1: Boundary Layer Profile Comparison

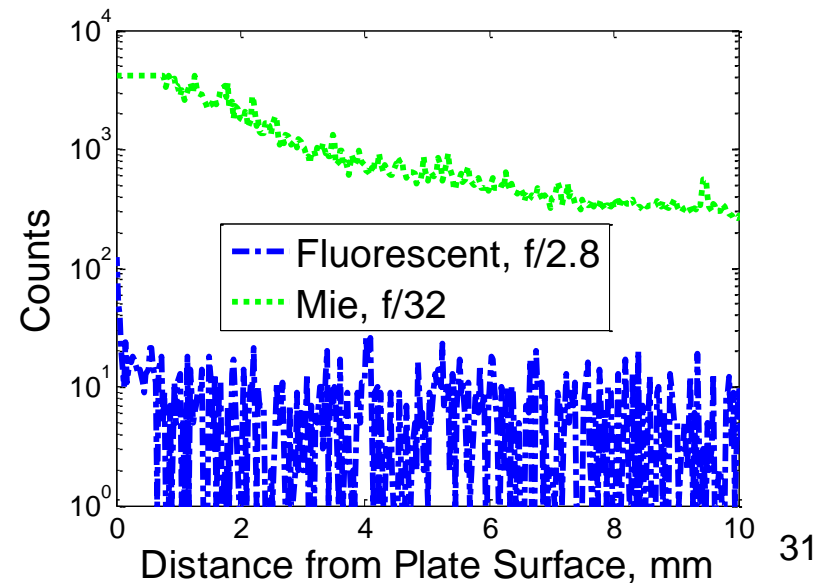


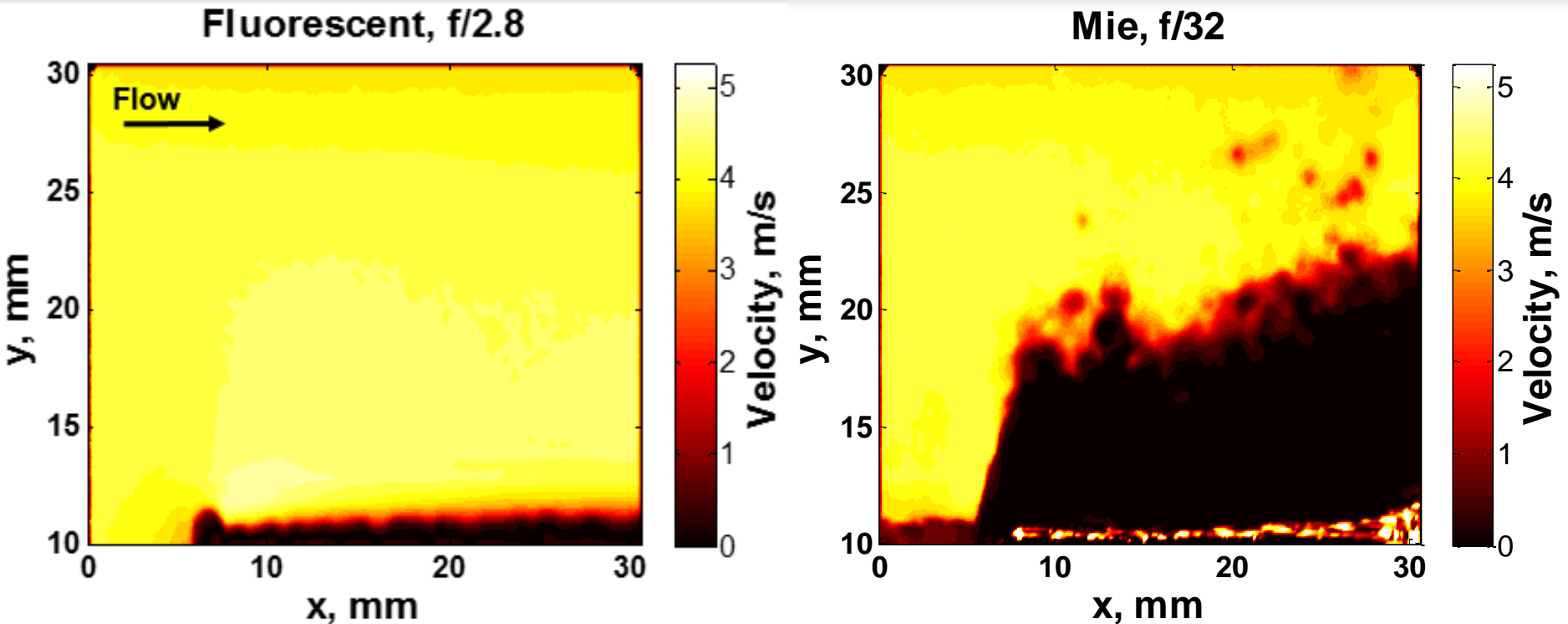
- The profiles were compared to Falkner-Skan boundary layer profiles.
- Falkner-Skan solutions set a pressure gradient through β .
 - Best fit for $\beta = -.13$.
- Mie PIV at f/2.8 and f/22 inaccurate within 1 mm and 0.5 mm of plate surface, respectively.
- Fluorescent PIV accurate to plate surface.

Plate Orientation 2: Angled Plate Images



- Plate angled 45° to laser sheet and camera.
- Significant flare in Mie images.
- Overall fluorescent background signal is 2+ orders of magnitude lower.

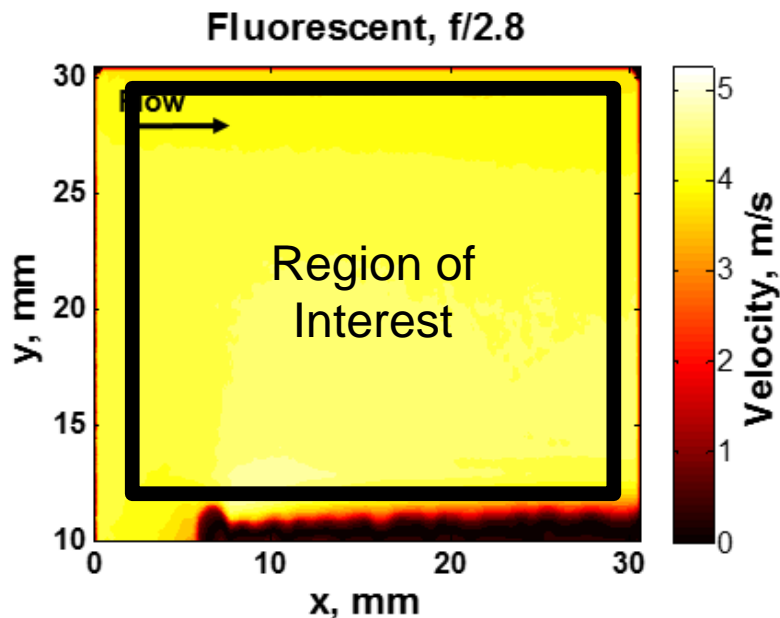




- 32 x 32 final pass interrogation window sizes.
- The stream-wise velocity averages above are calculated from only valid vectors.
- The Mie-scattered velocities are erroneous within 5-10 mm of the plate surface.

Plate Orientation 2: Angled Plate Validation Rates

- Validation rates compared for 100 images.
- “Valid” vector:
 - High peak ratio
 - Passes median filters
 - Stream-wise velocity between 2 and 7 m/s.
- 63 times fewer spurious vectors with Mie-scattered PIV.



Technique	Percent Valid, $Q > 1.3$	Percent Valid, $Q > 2$
Fluorescence	99.0%	95.1%
Mie	36.6%	24.7%



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5. *Kiton Red Temperature Sensitivity*

Initial Studies into the Temperature Sensitivity of Kiton Red PSL Particles

B Petrosky

- Intensity of fluorescent light:

$$I_{\lambda} = I_0 \alpha(\lambda_0, T) \varepsilon(\lambda, T) N_M$$

- The recorded fluorescent intensity at a given wavelength can be written as:

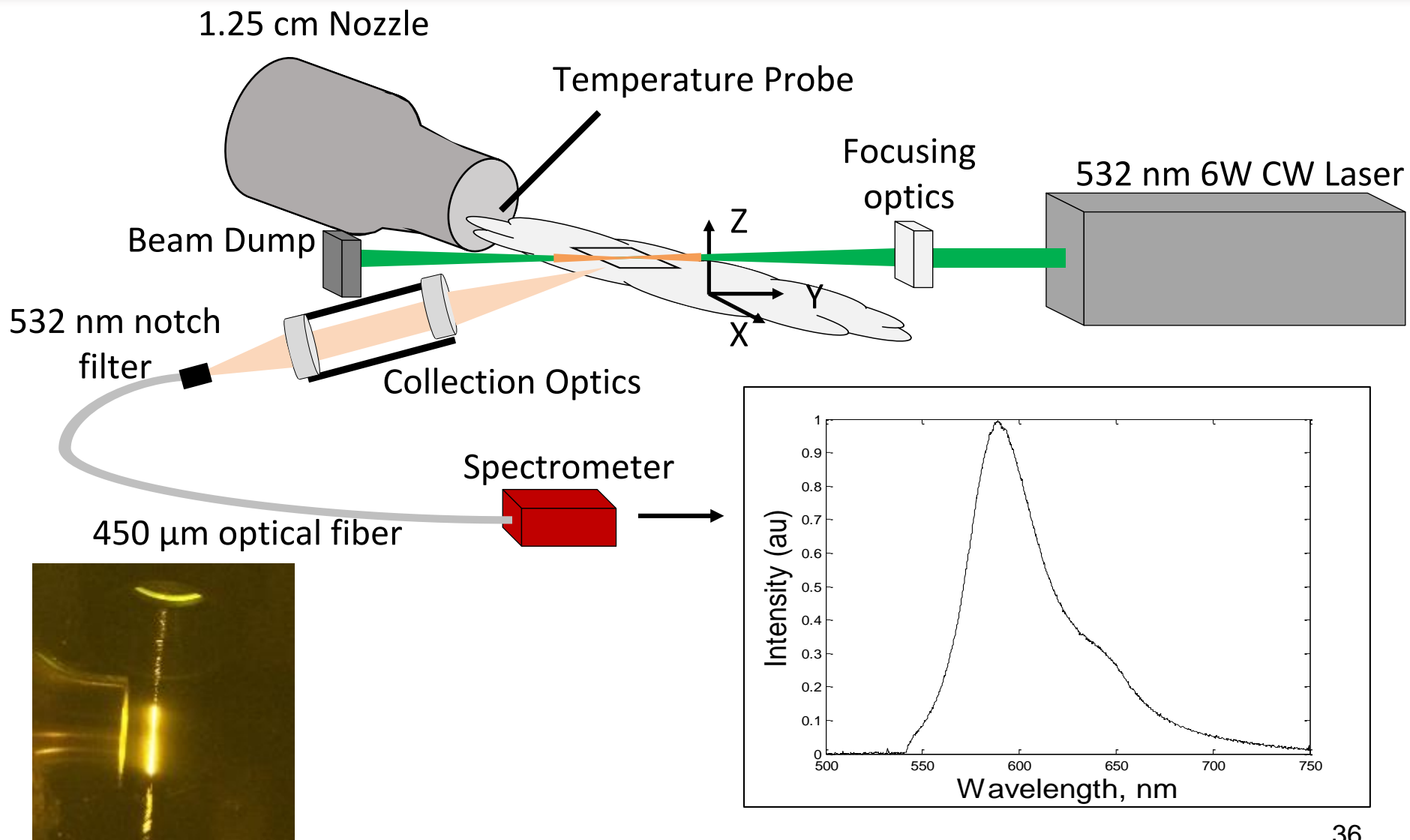
$$I_f = K_{opt} K_{spec} I_0 N_M e^{\left(\frac{\beta(\lambda, T)}{T}\right)}$$

- A ratio between two wavelength bands taken to eliminate parameters.

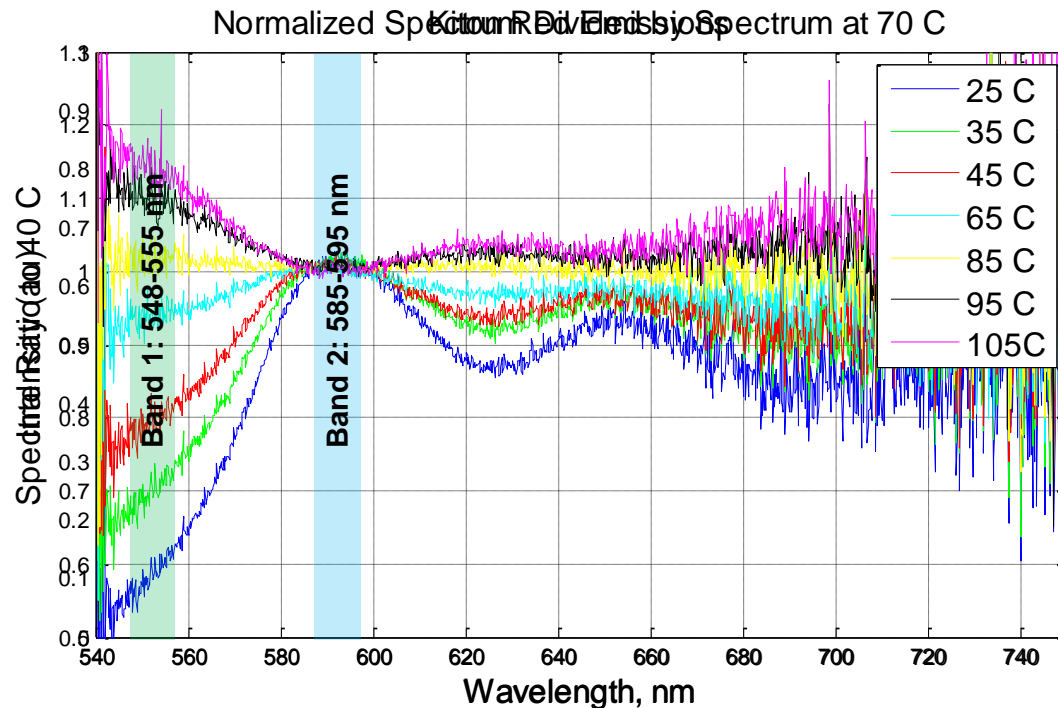
- This ratio has been shown to be of the form: $R_f = e^{\left(\frac{A}{T^2} + \frac{B}{T} + C\right)}$

- Temperature calculations using this method are well documented, with measurement uncertainties under 1-2°C [11].

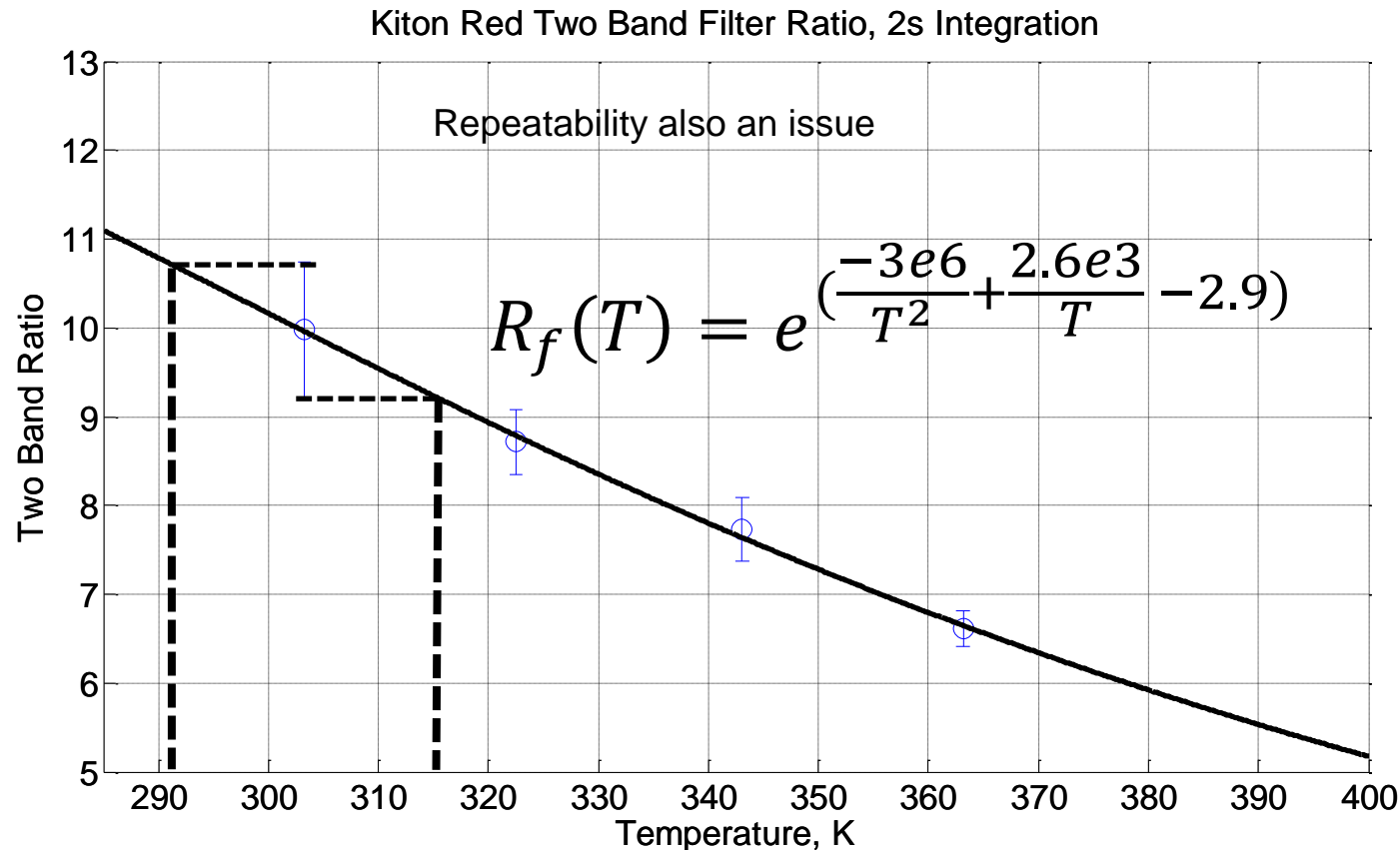
Experimental Setup for Calibration



- Tests at room temperature up to 110°, near the particle melting point.
- Spectrometer recorded over a finite period, usually 1-2 s.
- Spectra corrected for sensitivities at different wavelengths.
- Bands selected based on differing temperature sensitivities
 - Further optimized to maximize the two band ratio's temperature sensitivity.



- 10 spectra each obtained at 30°, 50°, 70°, and 90° C
- The ratio $R_{f,e} = \frac{B_1}{B_2}$ was taken for each measurement
 - B is the integral of the total measured signal for band



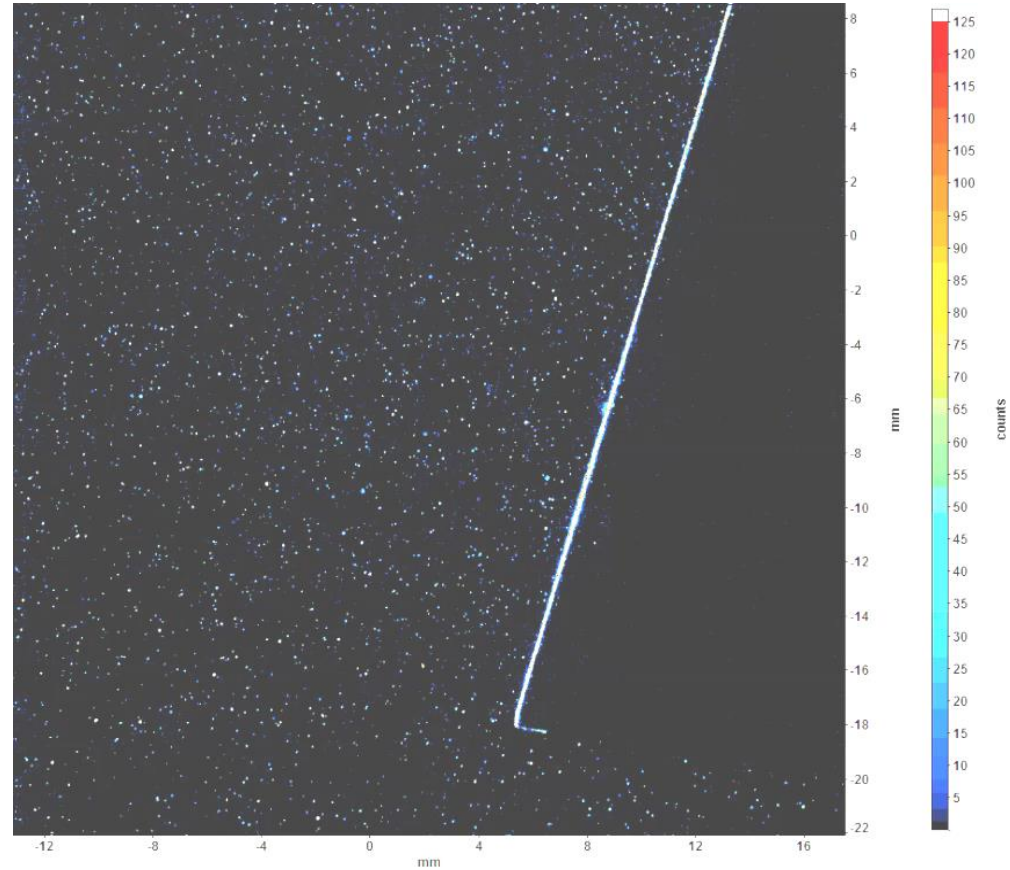
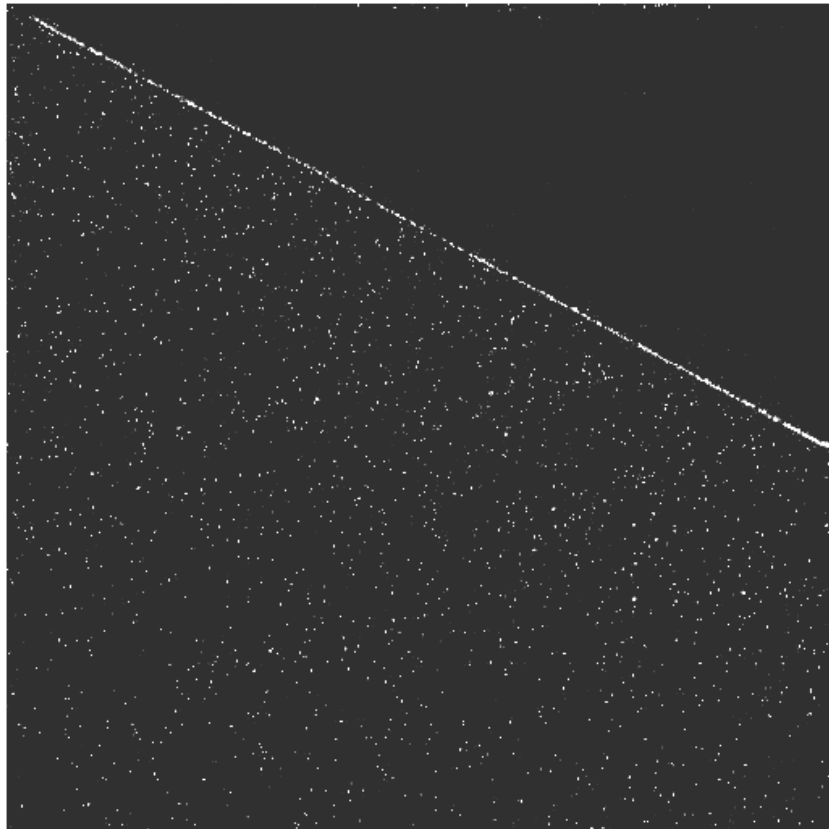
6. Work Summary

- Kiton Red doped PSL particles used meet all requirements of the research.
- Fluorescent particle signal calculated at 321 ± 12 times weaker than the Mie signal.
- Using LIF for PIV eliminates flare at surfaces or gas/liquid interfaces.
 - Over 0.5 mm closer to obstacle surface for minimal reflection case.
 - Over 5-10 mm closer to obstacle surface and 63x fewer spurious vectors for high reflectivity case.
- Kiton Red PSL's did not exhibit sufficient temperature sensitivity.
- Future Work:
 - Improvements in particle polymerization to increase fluorescent signal.
 - Larger scale applications- the end goal is for the ability to use these particles in any PIV or particle tracking application.

Special Thanks

- In addition to the co-authors of this paper, whose contributions were essential to the success of this work, I would like to thank the support of the NASA ARMD Seedling Fund and NIA Cooperative Agreement NNL09AA00A for making this research possible, as well as Max Verkamp and Jason Danley for their efforts in particle manufacturing and characterization.
- Also, a special thanks to all friends and colleagues in the CREATE center, whose day-to-day work and conversations taught me so much about how to conduct quality research and allowed me to develop my project as I did.

Questions?



- [1] Alexander, W. N., Devenport, W., Wisda, D., Morton, M., and Glegg, S. A. L., "Sound Radiated from a Rotor and Its Relation to Rotating Frame Measurements of Ingested Turbulence", 20 AIAA/CEAS Aeroacoustics Conference, Atlanta, GA, July 16-20, 2014, AIAA-2014-2746.
- [2] Poussou, S., and Plesniak, M. W., "Near-Field Flow Measurements of a Cavitating Jet Emanating From a Crown-Shaped Nozzle"
- [3] Lozano A, Barreras F, Fueyo N and Santodomingo S, "The Flow in an Oil/Water Plate Heat Exchanger for the Automotive Industry"
- [4] Wereley S and Meinhart C D, "Recent Advances in Micro-Particle Image Velocimetry"
- [5] Singh A K, Cummings E B and Throckmorton D J, "Fluorescent Liposome Flow Markers for Microscale Particle-Image Velocimetry"
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- [7] Chennaoui, M., D. Angarita-Jaimes, M. P. Ormsby, N. Angarita-Jaimes, E. McGhee, C. E. Towers, A. C. Jones, and D. P. Towers. "Optimization and evaluation of fluorescent tracers for flare removal in gas-phase particle image velocimetry." *Measurement Science and Technology*, Vol. 19, no. 11 (2008): 115403.

- [8] Hitt, David. "What are Wind Tunnels?" *NASA Education*. <[www.NASA.gov](http://www.nasa.gov)>
- [9] Walker, Martin. "Sulforhodamine B." *Wikipedia, The Free Encyclopedia*.
<http://en.wikipedia.org/wiki/Sulforhodamine_B>
- [10] Adrian, R and Westerweel, J. *Particle Image Velocimetry*, Cambridge University Press, New York, 2011.
- [11] Dunand, P, Castanet G, and Lemoine, F. "A Two-Color Planar LIF Technique to Map the Temperature of Droplets Impinging onto a Heated Wall."